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FINAL REPORT

PHOTOGRAPHIC AND PHOTOGRAMMETRIC METHODS OF TERRAIN ANALYSIS FOR DETERMINATION OF AIRCRAFT LANDING SITES

Prepared for

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

Contract AF 19(628)277
Project 8623
Task 862309

June 8, 1962

Itek
LABORATORIES

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FINAL REPORT

PHOTOGRAPHIC AND PHOTOGRAMMETRIC METHODS OF TERRAIN ANALYSIS FOR DETERMINATION OF AIRCRAFT LANDING SITES

Itek Corporation
Palo Alto Division
Palo Alto, California

June 8, 1962

Prepared for

Geophysics Research Directorate
Air Force Cambridge Research Laboratories
Office of Aerospace Research
United States Air Force
Bedford, Massachusetts

Contract AF 19(628)277

ABSTRACT

This report constitutes an investigation of several terrain analysis systems and techniques designed to evaluate the suitability of land areas for aircraft landing operations. This research was performed for the Geophysics Research Directorate of the Air Force Cambridge Research Laboratories by the Palo Alto Division of Itek Laboratories. The investigations encompass stereophotographic systems, including photographic interpretation and stereophotogrammetry, and spectral reconnaissance systems, including infrared detectors and spectral cameras. Recommendations are given for a program designed to test the performance of the equipment and techniques developed.

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A. INTRODUCTION

Of major importance in the terrain analysis of possible sites for aircraft landing operations is the determination of the surface roughness of those sites. The purpose of this investigation is to evaluate the stereophotographic techniques of photographic interpretation and photogrammetry as means for measuring this roughness. Photo interpretation has been defined as the determination of the nature and description of objects that are imaged on a photograph, and photogrammetry as the science or art of obtaining reliable measurements by means of photography. To meet the requirements of the proposed application, these techniques must afford positive identifications and accurate measurements of three- to six-inch terrain elevation changes with photography taken from altitudes of 10,000 to 25,000 feet.

In Section B the principles of stereoscopy and the procedures involved in stereoscopic photo interpretation and stereophotogrammetry are discussed. This will provide a background for readers unfamiliar with these fields. The error contributions or factors which determine the precision of these techniques are briefly described in Section C. These errors are the basis for the photographic and photogrammetric systems analyses in Sections D and E. Through the analysis of each of these systems, the required equipments and techniques are derived which will perform the proposed task. A test procedure designed to substantiate these theoretical concepts is described at the end of this report.

B. STEREOPHOTOGRAPHIC TECHNIQUES

1. Photography

The capability for determining terrain elevation differences through stereoscopic aerial photography is primarily based on the central perspective geometry of the photographic image. It is the nature of this geometry that: (1) a change in the position of the camera will cause an apparent change in the position of the object (Figure 1a), and (2) an elevation difference in the terrain will cause an image displacement or "relief displacement" in the photographic image (Figure 1b).

As can be seen from these figures, the apparent change in the position of an object will occur only in a direction parallel to the flight direction. The relief displacement effects, however, will occur radially about the nadir point of each photograph.[1] It is the combination of this apparent change in the position of the object and that component of the relief displacement that is also parallel to the flight direction that constitutes the basis for the stereoscopic determination of elevation differences. This combination is illustrated in Figure 2.

For this illustration, we have assumed truly vertical photographs taken with a focal length f, at a flight height H, and with a horizontal separation or base distance b. The combination of the stereoscopic

[1]The nadir is the photographic image of an object point which lies vertically below the camera lens. In the case of truly vertical photography, this point will correspond approximately with the principal point or center of the photograph.

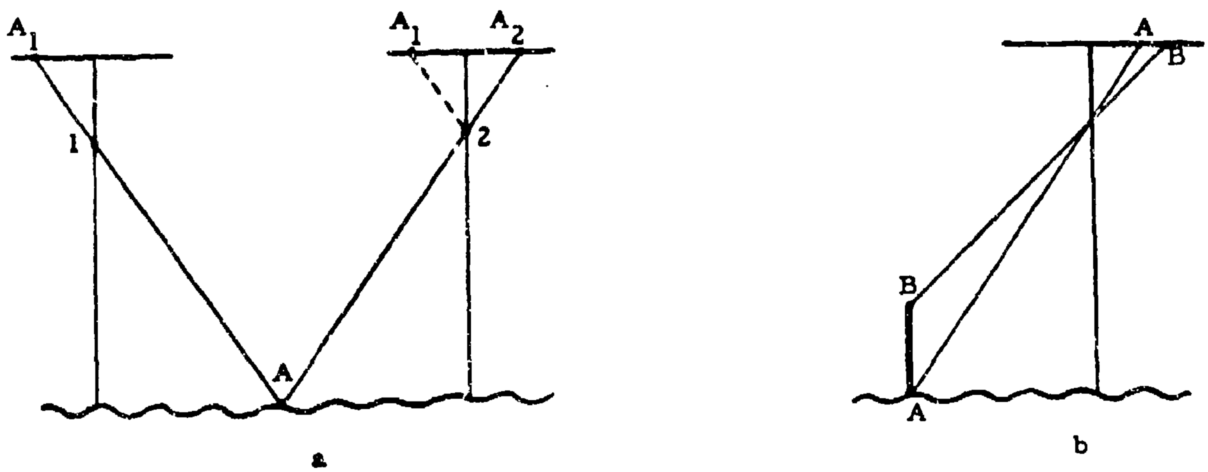

Figure 1 - FORMATION OF STEREOSCOPIC PARALLAXES

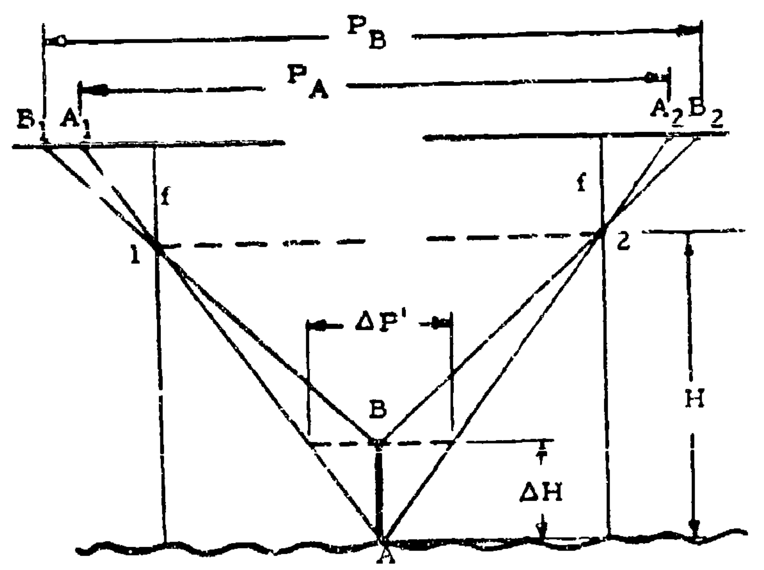

Figure 2 - GEOMETRY OF STEREOSCOPIC PARALLAXES

effects mentioned above for each of the two points (A and B) are termed stereoscopic or horizontal parallaxes (P_A and P_B). The parallax for each point is directly dependent on the distance from the cameras to that point. Accordingly, the parallax difference between two image points (P_B - P_A) is a measure of the distance difference or elevation difference (ΔH) between the points. This relation is derived below.

Let the parallax difference in the image P_B - P_A be denoted by ΔP; then through similar triangles it can be found that the parallax difference in the terrain $\Delta P'$ will be related to ΔP by the expression

$$\Delta P' = \frac{\Delta P(H - \Delta H)}{f} \qquad (1)$$

Again, through similarity

$$\frac{\Delta H}{\Delta P'} = \frac{H}{b} \qquad (2)$$

Substitution of expression 2 into 1 will give

$$\Delta H = \frac{\Delta P(H - \Delta H)H}{bf} \qquad (3)$$

or

$$\Delta H = \frac{H^2}{bf} \Delta P - \frac{H \Delta H}{bf} \quad \Delta P$$

Equation No. 3 is the general relation by which parallax differences observed and measured in the stereoscopic images may be related to their corresponding terrain elevation differences. In regard to the following analysis in which the value ΔH is to be extremely small, i.e., $\Delta H = H \times 10^{-5}$, the second term of Equation No. 3 will be negligible and the expression may be simplified to

$$\Delta H = \frac{H^2}{bf} \quad \Delta P \qquad (4)$$

Equation (4) is a simplification or approximation of the general equation and relates specifically to flat terrains on which only very small elevation difference will be measured. These relations, or others derived in a similar manner, are the basis of all stereoscopic determinations of terrain elevations and elevation differences. The slight variations which occur between the various methods of photo interpretation and photogrammetric techniques result only from the way in which stereoscopic vision of the images is established and from the manner in which measurements of the parallaxes are obtained.

2. Stereoscopic Vision

The three-dimensional impression or depth perception afforded by stereoscopic photography is obtained in much the same way as that impression obtained in natural binocular vision. (Binocular vision is specified to differentiate this analogy from the depth perception obtained through a comparison of object colors and sizes; this latter being as easily obtained with one eye as with two.) When an observer looks at various objects in space, his eyes converge and focus on each object. If all the objects occur the same distance from the observer, the angle of convergence of the observer's eyes will not change when he looks from one object to another. However, if the objects occur at varying distances, the angle of convergence of his eyes will also vary. It is this change in the convergence of the eyes which gives the observer a binocular impression of depth. Such a change in the convergence of the eyes will also be evident when viewing parallax differences in stereoscopic photography.

Stereoscopic photography may be viewed in a variety of ways. The most common procedure in photo interpretation is to observe positive prints of the photographs directly. Although this method is also used in some photogrammetric procedures, the most widely used technique is that of viewing projections of the photographs. The resulting three-dimensional effect is the same. The basic prerequisite for both of these techniques is also similar: that the images on both photographs be viewed simultaneously, each with one eye.

Figure 3 illustrates the manner in which the distance between the common image point in each of the photographs (parallax) will regulate the angle of convergence of the observer's eyes and thus the distance at which the stereoscopic image will appear. Image points with larger or smaller parallaxes will then appear nearer to, or farther from the observer. Figure 4 illustrates the similar effect which occurs when the observer views the horizontal parallaxes as they are reproduced by a projection system.

Through either of these methods of observation, a three-dimensional or stereoscopic model of the terrain will be presented to the observer. It should be noted, however, that the convergence of the observer's eyes is possible only in a direction parallel to his eye-base, and that the parallax differences which represent terrain elevation differences are those which occur parallel to the flight direction or air-base. Proper stereoscopic vision will be maintained, therefore, only so long as both the observer's eye-base and the parallaxes remain parallel to the flight path.

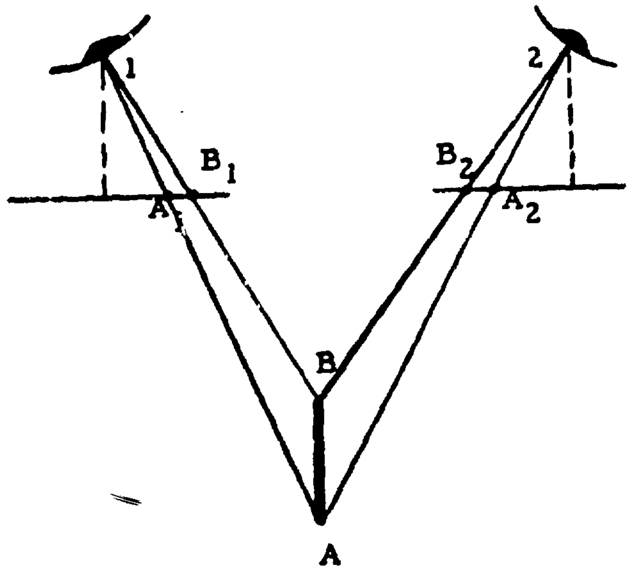

Figure 3_ DIRECT STEREOSCOPIC VISION

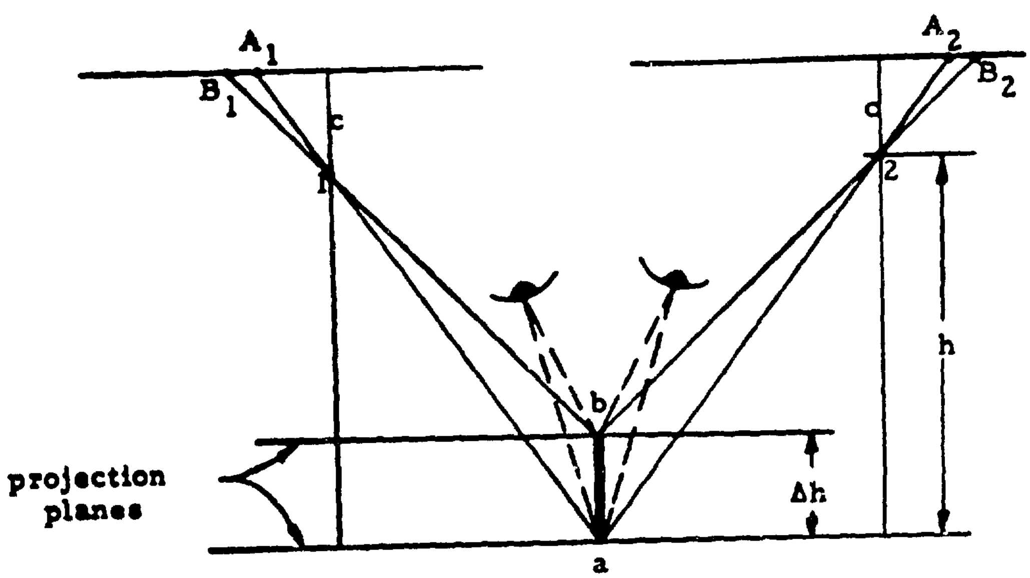

Figure 4_ PROJECTION STEREOSCOPIC VISION

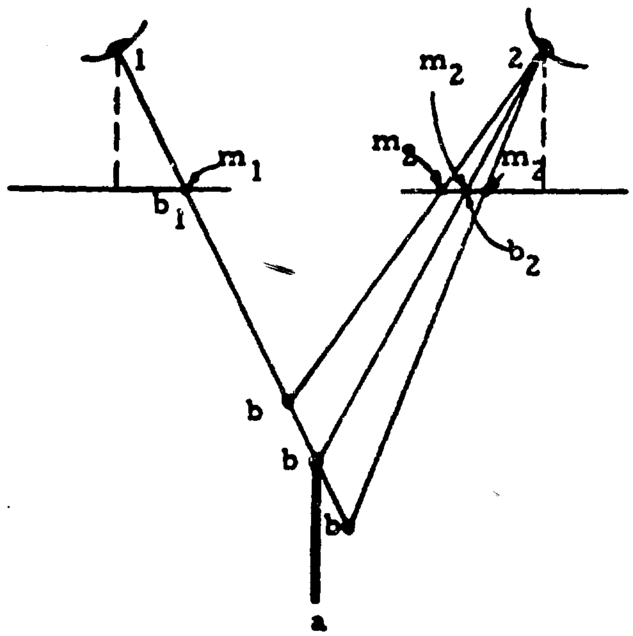

Figure 5— PARALLAX MEASUREMENT

3. Elevation Measurements

a. Direct Viewing

As was illustrated in Figure 3, the horizontal parallax of a point, the distance between its images in the two photographs, is a measure of the distance from the observer at which the point will appear in the stereoscopic model. Similarly, if marks other than the photographic images are placed on the photographs, one on each picture, the distance between these marks will control the distance at which they will appear as one mark in the stereoscopic model. Changes in the separation between these marks will then result in vertical changes of the single mark as seen in the model.

When each of the marks coincides exactly with the image of a given point in each photograph, the separation between the marks will equal the parallax of that point and the single mark will be seen to coincide vertically with the same point in the stereoscopic model (Figure 5).

If the distance between the marks is greater than the parallax of the given point, the single mark will appear at a greater distance from the observer, or below the given point in the model. Similarly, a shorter distance between the marks will cause the single mark to appear above the stereoscopic image of the given point. Thus, it can be seen that when the "floating mark" is made to rest precisely on the image point in the stereo model, i.e., at the same distance from the observer, the distance between the marks on the photography is an accurate measure of the horizontal parallax for that point. The difference between two such

parallax measurements will, therefore, give an exact measure of the parallax difference between the two points in question and through Equation No. 4, a measure of the true terrain elevation difference.

b. Projection Viewing

It can be seen from Figure 4 that the size of a horizontal parallax, as reproduced in a projected stereo model, will be dependent upon the projection distance or the separation between the projectors and the projection plane. Therefore, if the projection distance is varied, by placing the projection plane nearer to, or farther from the projectors, the size of the parallax of each point in the model will vary accordingly. It follows then that a projection distance can be found for each point in the model for which the parallax at that point will be zero. The difference between the projection distances required to eliminate the parallax at two points will be an accurate measurement of the elevation difference between these two points in the model. These elevation differences (Δh) can be related to the true terrain elevation difference by the equation

$$\Delta H = \frac{H}{f} \cdot \frac{c}{h} \cdot \Delta h \qquad (5)$$

where c is the principal distance of the projectors and h the mean projection distance from the model.

In order to maintain a correct geometric relation between the projected model and the actual terrain, the principal distance of the

projectors must be equal to the focal length of the taking cameras. Equation No. 5 will then simplify to:

$$\Delta H = \frac{H}{h} \cdot \Delta h \tag{6}$$

The precision of the stereoscopic vision and the precision of either photogrammetric measuring technique will depend on the accuracy with which the geometry of the stereoscopic model represents that of the terrain. This in turn is dependent on the relative orientation of the photographs or their projections in forming the stereo model, and the absolute orientation of the model scale and elevation reference plane to that of the terrain.

4. Relative Orientation

As each photograph is exposed, the plane of the photograph will have a given orientation relative to an assumed spatial coordinate system. This orientation can be defined by the three linear coordinates of the perspective center (the camera lens), and by three rotations of the photograph about this point. The three rotations are commonly measured with respect to the fiducial axes of the photography and the optical axis of the lens. Each photograph will then have six degrees of freedom in the given coordinate system (Figure 6).

If two such pictures are viewed stereoscopically, while their six freedoms have the same relative positions as they had at the time of

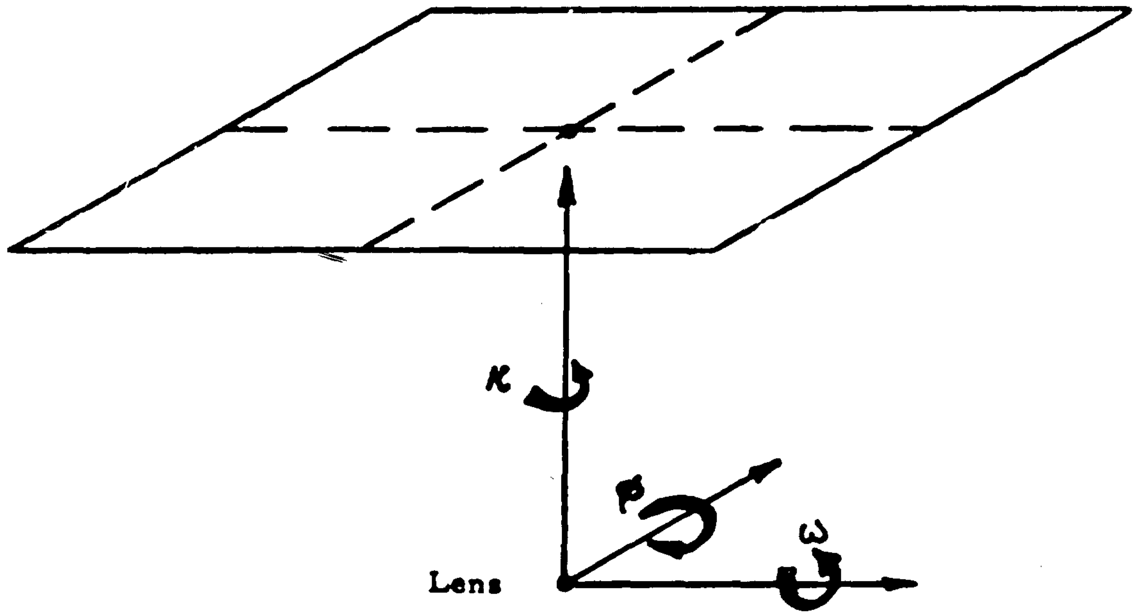

Figure 6— ELEMENTS OF RELATIVE ORIENTATION

exposure, a theoretically perfect stereoscopic model will be formed. In this event, all the image points on both photographs will have the same relative positions as at the time of exposure. Therefore, all the parallaxes between points will be exactly parallel to the flight path or the direction of the separation between perspective centers. If one or more of the relative positions of the freedoms are in error, this will no longer be true. In exception to this are the translations in the direction of flight; these translations will have the effect of only changing the scale of the stereoscopic model. Relative errors in the remaining freedoms, however, will introduce displacements between image points common to both photographs. These displacements will have components in the direction of flight and in a direction normal to this, and will vary according to the position of the points in the photographs.

The displacements normal to the flight path (vertical parallaxes), will cause difficulty in obtaining proper stereoscopic vision. These displacements, being normal to the observer's eye base, can be accommodated for by the observer's eyes only up to a limit of about one degree of arc. The size of the displacements corresponding to this limit are obviously dependent on the distance from which they are viewed. Vertical parallaxes in excess of this limit, however, will make stereoscopic vision impossible. The displacements occurring in the direction of flight will be parallel to the horizontal parallaxes and will introduce errors in these parallaxes.

The detection and correction of errors in the relative positions of the freedoms of the two photographs implies establishing a relative orientation of the photographs or of their projections. The requirements

for a relative orientation or the precision with which the vertical parallaxes and the errors in the horizontal parallaxes must be eliminated will vary between photo interpretation and photogrammetric techniques. In photo interpretation procedures where very approximate, if any, measurements are made of the horizontal parallexes,only proper stereo vision is required. This means that only the vertical parallaxes need be eliminated, and this only for each point in the model at the moment it is being observed.

The direct viewing procedures commonly employed in photo-interpretation are performed with the photographs lying in one plane, as on a table top, and no means for introducing the correct tilts to the photographs are available. Therefore, the vertical parallaxes can be removed from the stereo model only by a relative translation of the photographs in a direction normal to the flight path. These parallaxes will be found to vary with each image point and a correcting movement required for each point. This continual correction of the vertical parallaxes, required to maintain stereoscopic vision, makes the use of tilted photography very undesirable for photo interpretation work. This, however, refers only to accidental or random tilts. Known intentional tilts, introduced in convergent or oblique photography. can be removed through photographic rectification.

The relative orientation requirements for photogrammetric procedures are much more stringent than those for photo interpretation. The accuracy of the photogrammetric measurements of the horizontal parallaxes will be dependent on the accuracy with which the orientation errors can be removed from these parallaxes. Therefore, it is necessary

to eliminate the vertical parallaxes to obtain proper stereoscopic vision and also to correct the horizontal parallaxes. For this reason, photogrammetric procedures provide the ability to correct both of these effects.

These corrections can be found for a particular system through known geometric relations between errors in the freedoms of each photograph and the effects these errors will have on the stereo model. For example, with near vertical photography, the relation between the vertical parallax at a point in the model and the errors in the freedoms of the left-hand photograph will be

$$P_v = x dk_1 - \frac{xy}{h} d\varphi_1 + \left(1 + \frac{y^2}{h^2}\right) h dw_1 + \frac{y}{h} dbz_1 - dby_1 \qquad (7)$$

where x and y are the coordinates of the point as measured from the principal point of the photograph or its projection. The h is the projection distance when a projected model is observed or the focal length of the photogr .phy when it is viewed directly. A similar relation for the errors in the horizontal parallaxes would be

$$P_s = -y dk_1 - \left(1 + \frac{x^2}{h^2}\right) h d\varphi_1 + \frac{xy}{h} dw_1 + \frac{x}{h} dbz_1 \qquad (8)$$

The corrections to the freedoms of the photographs can be found by measuring the vertical parallaxes at selected points in the model and performing a simultaneous solution of relations similar to Equation No. 7. Excepting the translation in the x direction (direction of flight), which is used only for changing the scale of the model, there will be a

minimum of five freedoms (Equation 7) which must be corrected. Therefore, the vertical parallaxes must be measured at a minimum of five points in the model. In general, a total of six or more points are used in order to obtain sufficient redundant observations to perform a least square adjustment of corrections.

In a system where the projections of the photographs are viewed, these corrections may be introduced directly by changing the freedoms of the projectors. The model will then be free of vertical parallaxes and errors in the horizontal parallaxes. In the case where the photographs are viewed directly, no possibility exists for directly introducing corrected tilts to the photographs. In these systems, the horizontal parallaxes are measured simultaneously with the vertical parallaxes and the tilt corrections computed from equation No. 7 are used to correct the horizontal parallax measurements through equation No. 8.

5. Absolute Orientation

The stereoscopic model formed by the relative orientation of the two photographs may theoretically be formed at any scale and at any spatial position. To accurately relate the elevations measured in such a model to their true elevations on the terrain, both the scale of the model and the relation between the elevation reference plane of the model and that of the terrain must be known.

a. Scale

If parallax measurements are made directly on the photographs, as in the direct viewing procedure, the scale of these measurements

will be equal to that of the photography. When terrain elevations are measured in a projected model, the scale of these measurements is determined by the scale of the photography and the model projection distance. In either case, the scales must be accurately known.

If no ground control information is available, the scale of the photography must be computed from very accurate focal length and flight height determinations. The scale of the projected model will also require an accurately determined projection distance. In the event that ground control is available, the photo scale can be found by comparing the distance between two known points on the ground to the same distance as measured on the photography. The scale of the projected model may be determined directly by comparing the known distance to that measured in the model.

b. Leveling

The vertic reference plane from which elevation measurements are made in either of the techniques described is determined by the coordinate axes of the mensuration equipment. To properly relate the vertical reference of the instrument to that of the terrain will require knowledge of the terrain elevations of at least three non-colinear points in each model. A comparison of the elevations measured from the instrument reference to those measured from the ground reference (sea level) will give an indication of the relative spatial orientations between these planes.

6. Summary

The measurement of elevation differences in a projected stereo model can be seen to be a much more direct solution than the measurement of horizontal parallaxes on the photography. Following a proper relative and absolute orientation of such a model, the elevations or elevation differences may be measured directly for any and all points in the model. The rapidity of the projection solution can be further enhanced by adjusting the vertical scale on which the model elevations are measured to read directly in the desired units at ground scale, thus eliminating the $\frac{H}{h}$ factor in Equation 6. This system is used in most photogrammetric procedures in which topographic maps showing the approximate elevations of all points in the model are desired.

Though the elevation measurements obtained through a direct viewing system are generally somewhat more accurate, the presentation of these measurements is not so immediate. As was indicated previously, the measurements required for the relative and absolute orientations are performed simultaneously with the measurements of the horizontal parallaxes. Through one computation, normally using an electronic computer, the horizontal parallaxes are corrected for the relative and absolute orientations and then reduced through Equation 4 to terrain elevations. This system, therefore, requires a parallax measurement for each and all of the points desired before any reduction of these measurements is performed. The terrain elevations or elevation differences of a selected few points cannot be obtained easily until all the points which are to be measured have been measured. The direct

viewing system is commonly used only when the elevations of a limited number of points in each model are desired; the most frequent use being the extension of ground control points for leveling and scaling projected models.

C. ERROR CONTRIBUTIONS

1. Image Interpretability

Because both the photographic interpretation and photogrammetric procedures are based on a visual analysis of a stereoscopic model, the precision of each of these will be dependent on the interpretability of the photographic image. This interpretability will regulate the certainty with which small elevation changes can be detected, and the reliability with which the cause of the changes can be determined. The precision of the photogrammetric measurements will also be limited by the interpretability of the images because regardless of the precision of the mensuration equipment, the smallest elevation change which can be observed will partially determine the accuracy to which any individual elevation can be measured. The interpretability required of the photography to produce a desired reliability in interpretation and mensuration will be a prime factor in the selection of films, lenses, and other components of the photographic system.

2. Photogrammetric Measurements

Each step in the photogrammetric procedure involves some form of measurement in the stereoscopic model. These are namely: (1) the vertical parallax measurements performed during the relative orientation of the photographs, (2) the horizontal and vertical measurements of the control points used to scale and level the model, and (3) the horizontal

parallax or model elevation measurements for individual points in the model. These measurements will be influenced by both the visual perception of the observer as discussed above and by the inherent precision of the mesuration equipment. Although the occurrence of large accidental errors may be controlled by having several operators perform repetitive readings of each of the measurements, small residual errors will remain. These residuals, due mainly to instrumental errors, are the major considerations in the selection of mensuration equipment.

The effect on the determination of terrain elevation differences of the instrumental errors in the measurement of horizontal parallaxes and model elevations can be seen directly in Equations Nos. 4 and 6, respectively. These errors will have an equal effect on the measurement of all points and will be relatively independent of the position of the points in the model. The errors introduced through the relative and absolute orientation procedures will not be quite so regular. The errors in model elevations introduced by inaccuracies in the determination of the relative orientation of the photographs will be a systematic function of each freedom which is in error. The elevation errors for each point in the model, or the systematic deformation of the model as a whole, can be computed through the coefficients of each freedom in Equation 8. It is important to note that any one or a combination of these model deformations may occur, and the effect these will have on the measurement of elevation differences will be strongly dependent on the positions of the points in the model and the distance between the points.

In general, a leveling of the model is performed by rotating the model about an axis parallel to the direction of flight and about an axis

normal to this. Errors in the leveling will, therefore, result in a tilt of the model in either of these directions. The accuracy of the absolute orientation will be dependent on both the precision with which the elevations of the control points are measured in the model and on the precision with which the true terrain elevations of these points are known.

3. Geometric Errors

The relation between the parallax differences measured in the photography and their corresponding terrain elevation differences is expressed by Equation 4. This relation was derived from Figure 2. Although the photographic sequence is depicted in this figure by perfectly linear geometry, this is not actually true. The rays of light imaging each object on the film will not be straight, and neither the earth's vertical reference nor the film plane will be perfectly flat. Therefore, if Equation 4 is used unconditionally in the data reduction procedure, each of these deviations from the linear geometry of Figure 2 will be a possible source of error. Similarly, it can be shown that unless each projection is made to duplicate the geometry of the actual photographic sequence, the stereoscopic model formed by these projections and the reduction through Equation 6 will also be in error. The sources of these geometric errors are discussed below:

a. <u>Lens distortion</u> -

(an aberration affecting the position of images at different angular distances from the optical axis.)

From the above definition it can be seen that the displacement of image points due to lens distortions will be a function of their angular distance from the optical axis and will, therefore, be radial about the principal point or the intersection of this axis and the plane of the photography. These are determined through camera calibration procedures and subsequent corrections applied to minimize their effect.

The lens distortion for a given angular distance can be computed from Equation 9;

$$d = L - f \tan \alpha, \tag{9}$$

as derived from Figure 7. In conventional calibration procedures the angle α is measured with a goniometer and the distance L with a linear comparator, and a mean-square error for the computed distortion at a given point is found to be approximately 10 microns at the scale of the photography. However, in connection with ballistic missile photogrammetry, star calibrations have been performed in which errors of 5-6 microns have been obtained.

The corrections for the calibrated lens distortions are introduced in the projection systems through various optical and mechanical means. Although these corrections eliminate the major portion of the distortion, the devices themselves are only approximate and their errors plus that of the calibration may easily result in a total error of 10 microns.

The corrections applied in a direct viewing procedure are introduced as numerical corrections to the measured parallaxes and will,

therefore, have the same error as the calibration procedure; approximately 5 microns.

b. <u>Film distortion</u> -

(changes in the relative positions of image points due to dimensional changes in the film base and emulsion.)

Photographic films and emulsions will receive their greatest dimensional change from mechanical stresses applied during processing and from large variations in temperature and relative humidity. In projection systems, it is impossible to correct these random changes; they must be minimized as well as possible through proper selection of film base and by carefully controlled processing procedures. Consideration should be given here to the use of optically flat glass plates as the emulsion base.

For direct viewing systems, numerical corrections may be introduced into the measured parallaxes in the event that these dimensional changes can be detected. Such a control may be obtained by imaging a "reseau grid" on the photographs at the time of exposure. Any dimensional changes of the photographs after exposure can then be readily detected as changes in the grid pattern. This solution, however, is only applicable to the direct viewing procedure.

The use of glass plates in either system will effectively restrict the dimensional changes to only that of the emulsion which, in general, will be negligible. If the additional weight of the glass plates becomes

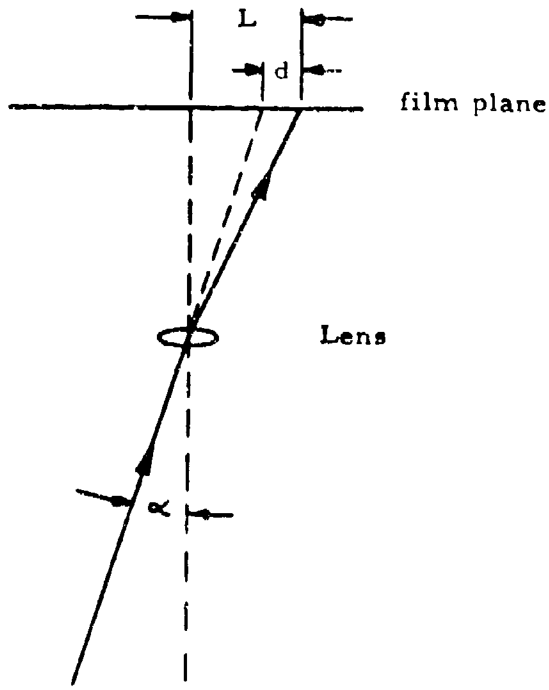

Figure 7. RADIAL LENS DISTORTION

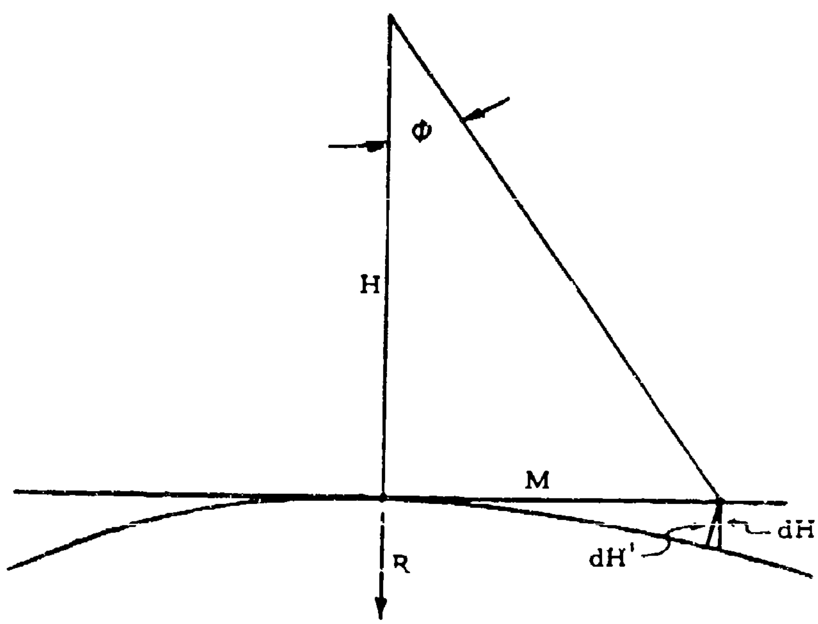

Figure 8. EARTH CURVATURE

a problem, the reseau system may be applied. In this case the measured corrections will include both the errors in the manufactured grid and in the measurement which may have a mean-square-error of about 3 microns.

Either of these techniques will also reduce the errors introduced by variations in the flatness of the film during exposure.

c. <u>Atmospheric refraction</u> - (displacement of the position of an image caused by the bending of the light rays as they pass through the earth's atmosphere.)

The refractive index of the earth's atmosphere will decrease with altitude as a function of the atmospheric density, and its bending effect on light rays will be a function of the angular distance from the vertical. These displacements will, therefore, occur radially about the nadir point of the photographs, as do relief displacements, and will depend on the angular tilt of the camera and its angular field of view. Through knowledge of the aircraft altitude and atmospheric conditions at the time of exposure, approximate corrections can be determined for these displacements. These corrections may be introduced into the parallax measur. ments in a direct viewing procedure. In general, however, no correction is possible for a projection system, although some attempts have been made to introduce these corrections in a manner similar to that used tor lens distortions.

d. <u>Earth curvature</u> -

(displacement of the position of an image as photographed on the earth's curved surface from the position it would have if the earth were considered to be a plane surface.)

The elevation measurements obtained through either a projection or direct viewing system are referred to an orthogonal coordinate system. If these are related directly through Equations 4 or 6 to terrain-elevations on the earth's curved surface, the resulting elevations will be in error. The error will be approximately:

$$dh = \frac{M^2}{2R} \quad \text{where } M = H \tan \phi \qquad (10)$$

as derived from Figure 8. This equation assumes the difference between dH and dH^1 to be negligible.

When the stereo model covers only a small portion of the earth's surface, as with relatively low altitude photography, the total elevation error dh or dh^1 may also be negligible. However, as the photography is taken with increasingly wider fields of view or from higher altitudes, these errors will become more significant.

In either of the phogrammetric techniques, necessary corrections ($-dh$ or $-dh^1$) may easily be introduced. The precision of these corrections will depend on the accuracy with which the values H and ϕ are known and on the correction equation used.

4. Summary

The ease and reliability of the photographic interpretation procedure will depend primarily on the quality of the photographic image and on the ability to obtain adequate stereoscopic vision. While these are also important in photogrammetric operations, a more significant factor will be the accuracy with which the geometry of the original photographic sequence can be reconstructed. The majority of the many error sources in the photogrammetric procedures result from inaccuracies in this geometric analogy.

It is important to note that while the image interpretability, instrumental errors and errors in model scale will influence elevation measurement of each point equally, the geometric errors and those of the relative orientation and model leveling will affect the measurements as a function of the position of the points in the model. It is evident, therefore, that two points within a close proximity of one another will receive approximately equal effects from the latter errors, and the resultant influence on the parallax difference or elevation difference between two such points will be negligible.

In the following sections, the photographic and photogrammetric requirements will be investigated for the proposed high-altitude applications of the techniques previously discussed. The photographic requirements will be discussed as they will influence the selection of the most appropriate camera and method of photography. The selection of photogrammetric equipment and techniques will then be based on the data reduction requirements for this photography. This photogrammetric

analysis will also be predicated by the assumption, that for the proposed application, the extremely high measuring accuracies required will apply only to abrupt elevation changes; gradual changes over greater horizontal distance will be less important and the reliability requirements less severe.

D. PHOTOGRAPHIC SYSTEMS

1. Photographic Requirements

a. Photographic Interpretation

In determining the nature and description of objects from aerial photography, photo interpretation entails three related processes: detection, recognition, and identification. These processes are rather well defined. Detection implies only the presence of an object (a blob) on the film. Recognition, a step beyond detection, implies that the shape of the object can be recognized and classified (circle, square, rectangle). Identification implies that the object can be named: example, a rectangle can be distinguished as a truck rather than a tank or a small building. These three processes, though primarily related to the interpretation of detail, may also refer to the stereoscopic interpretation of heights. In this application the three processes may imply the detection or ability to perceive that a change in elevation does exist and the recognition and identification of the object or cause of the change in elevation.

The level of interpretability of an object as imaged in the photography will have physical, psychophysical, and psychological components. Both the number and variability of the factors comprising these components make the problem of predicting the interpretability of an object very difficult. Figure 9 is a summary of these factors. Though not complete, this list indicates the complexity of the problem.

Object Space Factors	Factors that Affect Interpretability		
Length: Shape; Size (Area)	Physical (Inherent limits set by the physical characteristics)	Imaging Factors	Sharpness focus aberrations image motion Scale grain/detail grain/shape transfer function
Actinic Brightness: Exposure Level; Contrast		Photographic Factors	Gamma Exposure Transfer function Latitude Granularity Turbidity Printing and projection losses
	Psychophysical (Inherent limits set by the viewing process		Sharpness of image Contrast of image Scale of image Scale of viewing Graininess Shape of object Illumination in viewing Conditions of viewing projection vs. direct binocular vs. monocular stereo vs. non-stereo Observer comfort
	Psychological (Inherent limits set by the human being)		Acuity Experience Motivation Set Skill Intelligence Knowledge Environment

[1] After Macdonald (1958)

Figure 9 - FACTORS INVOLVED IN INTERPRETATION[1]

It is clear that identification is the most demanding of the interpretation steps and, therefore, will have the greatest dependence on each of these components. This is particularly true of the psychophysical and psychological factors. Detection and recognition will be less dependent on these two latter components and can be more easily defined, as they are controlled to a large extent only by the physical component. Therefore, the requirements for detecting and recognizing an object or parallax difference can be determined through their relation to the physical characteristics of the photographic system, while the requirements for a positive identification can be only estimated through experience and experimental tests assuming good viewing techniques and highly trained observers.

The physical component is comprised of those factors which will affect the information content or resolving power of the photography. The resolving power of a photographic system (R) describes the number of equal line and space pairs per millimeter that can be recorded and distinguished in the photographic image. Thus it can be said that the smallest detail which is just detectable in the photographic image will be of a size no smaller than one line or one space; or 1/2R, where I/R is in millimeters. Most observers agree that for an object to be recognizable it must be imaged at a size approximately five times greater, or 5/2R millimeters. Identification does not necessarily require a larger image size; it usually implies better knowledge or additional information about the terrain.

If these relations are again applied to the problem of interpreting terrain elevation changes, it may be reasoned that the smallest just detectable parallax difference will also be no smaller than 1/2 R millimeters. Aschenbrenner (1950) has indicated, however, that the size of this just detectable parallax difference may range from 1/2R to as low as 1/4R. This increase in the interpretability of parallax differences over that of detail is explained by the fact that a parallax difference is interpreted from a relative displacement between a group of detail representing an object and another group of detail representing the objects' background. This increase is greatly dependent, however, on the visual and psychological ability of the operator, and for our purposes we will assume the more conservative value of 1/2R as the smallest detectable parallax difference. A further analogy to the interpretability of detail discussed above would indicate that to recognize and identify the cause or source of the elevation change will require parallax differences of approximately 5/2R millimeters.

The level of interpretation required for a particular application will be determined by the reliability and completeness that is desired of the results. Detection is the minimum situation; strongly influenced by slight variations in the predicted resolving power. This will be a "Go" or "No-Go" procedure with a very low reliability. The reliability of the interpretation will increase with an increase in resolving power. Approximately a 5X increase in resolution will make objects previously only detectable now recognizable, and possibly identifiable. This is by no means an optimum situation, but the reliability of the interpretation afforded by this level of resolving power has proved sufficient for more

demanding applications. Considering the consequences of the proposed application, it may reasonably be assumed that these higher levels of interpretability would be desirable.

b. Photogrammetry

The accuracy of photogrammetric measurements is strongly dependent on the level of interpretability of the photography. This will be true of both planimetric measurements and the measurement of elevations and elevation differences. The influence of the level of interpretability of the images first becomes evident as it determines the reliability with which the observer can identify those points for which measurements are desired. In the present application, where the measurement of elevations and elevation differences are required, the interpretability of the photography will influence the observer's ability to locate those points or areas in the stereo model at which elevation changes exist. This preliminary step will require at least the minimum level of interpretability: Detection.

The influence of the level of photographic interpretability will next appear in the precision of the elevation measurements themselves. In the discussion of the measuring techniques it was shown that in both the direct viewing and projection systems, the elevations or parallaxes of individual points are determined by moving a floating mark up and down in the model until it rests precisely on the point in question. It may be reasoned, therefore, that the observer's ability to detect small elevation changes of the floating mark in the model will be no greater than his

ability to detect similar elevation changes in the model itself. Following this line of reasoning then, it may be assumed that regardless of the precision of the mensuration instrument the reliability of each elevation measurement will be limited to approximately $1/2R$ millimeters. Each elevation difference will be determined as the difference between two such elevation measurements and may be assumed to have a combined reliability of approximately $\sqrt{2}/2R$ millimeters. Because of the large variations which will exist between individual observers, however, a general assumption of this type cannot be accepted with a great deal of confidence. In the following discussions we will approximate this by $1/2R$ the level of detection of parallax differences. Though not definitive, this value will serve to illustrate that the level of interpretability required for just detecting a given elevation change is by no means sufficient to produce reliable measurements. A more exact value for the precision of these measurements, including instrumental errors, will be derived in Section E.

2. Photographic Resolving Power

The resolving power referred to in the preceding discussion is that of the final photographic image as obtained under dynamic or operational conditions. This resultant resolving power will be determined by the static or laboratory capabilities of the system and by the degradations of this which will occur during an actual flight.

	Target Contrast		
Film	1000:1	8:1	2:1
SO-132	417	309	243
SO-221	184	172	133
SO-130	154	138	110
SO-102	105	92	65

Figure 10— MAXIMUM RESOLVING POWER OF SELECTED FILMS

a. Static Resolving Power

The static resolving power of the system is determined through well known optical and photographic tests of its two basic components, the lens and the photographic emulsion. The purpose of these tests is to predict the capabilities of each component under various simulated flight conditions and, thereby, to aid in their selection for a particular application. In general, however, only those conditions are simulated which will directly effect the optical quality of the lens and the photographic chemistry of the emulsion; the main consideration being the illumination to be available and the relative brightnesses (contrast) of terrain features.

Of importance in the testing and selection of lenses for both photo interpretive and photogrammetric work is the limitation which a desired resolving power may place on the useful field of view of the camera. Theoretically, the maximum resolution of the lens will occur along its optical axis and will decrease as a function of the angular separation from this axis. This can be seen in conventional six-inch cartographic cameras which vary in resolution from approximately 40-50 lines per millimeter on-axis to 10-20 lines per millimeter at the perimeter of a 9 x 9-inch format. The exact rate of the off-axis resolution loss will vary with specific lens designs. However, in cartographic cameras this is normally quite rapid.

The resolving power requirements to be developed in this investigation are those which will be required of all points in the photographic image, including those at the edges of the format. It is evident,

therefore, that in order to maintain the overall resolution as near the maximum as possible, the angular separation of images from the optical axis must be limited, thus limiting the field of view. The effects of the narrow fields of view required of high resolution systems and their correspondingly small ground coverage will be felt in the increased navigational precision required to obtain a pre-determined stereoscopic overlap between successive exposures.

Figure 10 shows the results of resolution tests performed by Itek Laboratories for a selection of high performance aerial films. These indicate that even under the low contrast levels of 2:1 and less, expected of most aerial photography, extremely high resolution films are available. Comparatively high resolutions are possible through present design and manufacturing capabilities for lenses with narrow fields of view. These values, however, refer only to the optimum situation where both lens and film are in a static or motionless position.

b. Dynamic Resolving Power

Even though the optical conditions encountered during an operational flight have been accurately simulated in static resolution tests, the predicted resolving power for a given lens-film combination will rarely be attained. This value will be severely degraded by photographic image motion during exposure, introduced by the dynamics of the aircraft, the camera mount, and the camera itself. The most evident of these image motions will be introduced by the relative velocity of the aircraft with

respect to the terrain. The displacement or blur of image points resulting from this can be computed through the relation:

$$\text{image motion blur} = \frac{f\ V\ t}{H} \tag{11}$$

where: V = the ground speed of the aircraft

T = the exposure time

Image motion compensation (IMC) for this velocity component may be accomplished in a variety of ways. The most common methods are to introduce compensating motions to the film, the lens, or the camera as a whole. The choice of the most appropriate system will depend on the purpose for which the photography is taken. In reconnaissance and interpretation procedures, the quality of the photographic image is the only criterion, and any of the various techniques may be used. Photogrammetric applications, however, require that the geometric relations between each point in the image and the nodal point of the lens be known. The accuracy of the photogrammetric procedures were shown to be dependent on the ability to reconstruct this geometry. For this reason, any IMC corrections which will introduce a relative motion between the film and the lens should be avoided. The remaining possibility for compensating the image motion by moving the camera as a whole, is more desirable. In this technique, the IMC should be introduced as a rotation of the camera about the nodal point of the lens.

Regardless of the method of IMC used, the correction will be open to various errors, such as variations in aircraft velocity and altitude,

and mechanical imperfection in the IMC apparatus.

Additional image motion components which will degrade the predicted system resolving power will be introduced by the mechanical vibrations of the aircraft, camera mount, and internal mechanisms in the camera itself. The displacement or blur of the image points resulting from these vibrations can be computed as:

$$\text{vibration blur} = 4\,AFt \quad \text{if} \quad t < \frac{F}{2}$$

$$\text{" \quad "} = 2\,A \quad \text{if} \quad t \geq \frac{F}{2}$$

where: A = the amplitude of the vibration

F = the frequency of the vibration

IMC for these vibration effects would be a very difficult undertaking. A more practical solution is to determine the various frequencies and amplitudes and apply adequate vibration damping or isolating techniques to remove their effects.

The vibrations introduced by the air-frame at the camera position should be measured while the aircraft is operating at the desired photographic speed, altitude and attitude. Through a proper selection of isolation equipment, the transmission of these vibrations to the camera may then be controlled.

The vibrations of the internal mechanisms of the camera itself will introduce a more difficult problem. These vibrations, due mainly to operation of the shutter motor and the film transport motor, are

easily detected and measured but not so easily eliminated.

The effects of the IMC errors and vibrations on the resolution of a particular system and the possibilities for improving this cannot easily be generalized. An intensive evaluation of the components of the candidate system, such as the aircraft, camera mount, camera, and film, will be required.

An example investigation of this type has been the KC-17 camera with a 24-inch focal length, mounted in a C-47 aircraft. (Harold 1958). This experiment showed that aircraft vibrations, when properly controlled by torquer stabilized camera mounts and coil-spring and dash-pot vibration isolators, did not degrade image resolution below approximately 100 lines per millimeter. The vibrations caused by the mechanisms of the camera and the camera mount, however, were found to have a more dramatic effect. This is illustrated in Figure 11.

In the following analysis, the photographic requirements, specifically the resolving power, will be determined for just detecting small terrain elevation differences from relatively high altitudes. These will be the minimum requirements with their correspondingly low reliability. It is understood that to obtain a positive identification of the cause of the elevation change and to obtain reliable measurements of the change itself will require resolving powers of some greater value. These minimum values are given because they are of a general nature; the higher level required for particular applications will vary greatly with the reliability desired of each procedure.

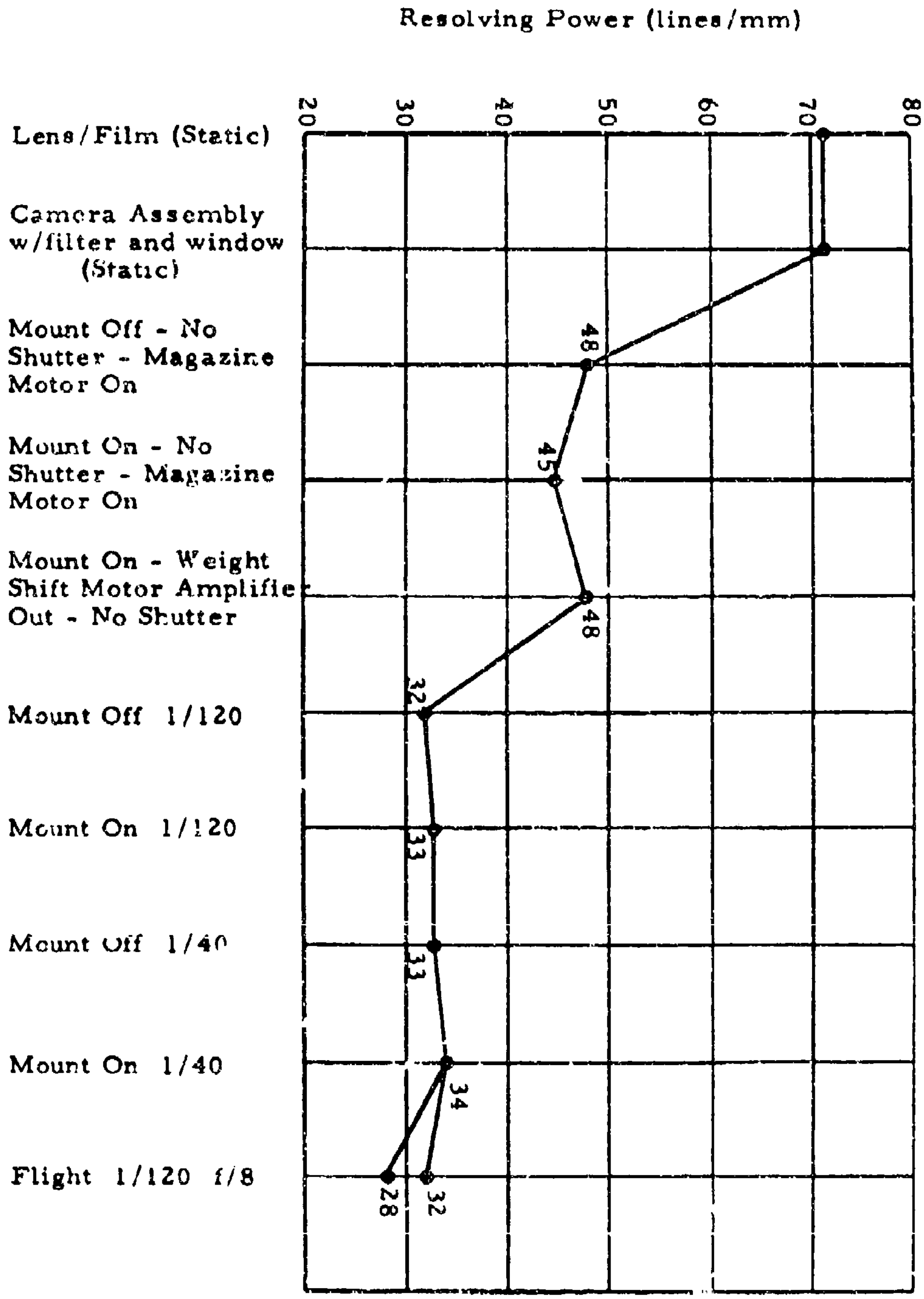

Figure 11 - THE EFFECT OF MECHANICAL FACTORS ON RESOLUTION

3. System Parameters

The basic photogrammetric relation between a parallax difference in the photographic image (ΔP) and its corresponding elevation change in the terrain (ΔH) was developed in Section B and found to be:

$$\Delta H = \frac{H^2}{bf} \quad \Delta P \qquad \text{[See (4)]}$$

By considering this relation in an optimum situation, where ΔP is equivalent to the minimum detectable parallax and ΔH is the corresponding minimum detectable elevation change, an identity can be derived between this smallest detectable parallax and the resolving power of the system. Such an identity was derived in the preceding section and this minimum ΔP was found to be approximately equal to the smallest resolved detail ($1/2R$) where R is in lines per millimeter. Equation No. 4 may be rewritten to include this function of the resolving power. This will give:

$$\Delta H = \frac{H^2}{bf} \cdot \frac{1}{2R} \qquad (13)$$

or:

$$\Delta H = \frac{H}{b} \cdot \frac{H}{f} \cdot \frac{1}{2R}$$

The terms H/b and H/f are the inverse base: height ratio, and the inverse scale factor, respectively. From this relation it can be seen that a photographic system designed to detect very small terrain elevation

changes will require:

(1) A large scale factor $\frac{f}{H} = S$

(2) A large base: height ratio $\frac{b}{H}$

(3) A high resolving power R

a. The scale factor for any point on an aerial photograph will be a function of the angle of tilt (t) of the optical axis from the vertical and the angular displacement of the point from the optical axis (d) in the direction of the tilt. This function will be:

$$S = \frac{f \cos (t + d)}{H \cos d} \tag{14}$$

It can be seen that in photography taken with a given angle of tilt, the scale factor of individual points in the image will vary according to their angular displacements (d). These angular displacements, when measured with the same sign convention as the tilt will range from $d = -\frac{\theta}{2}$ to $d = +\frac{\theta}{2}$ where θ is the angular field of view of the camera. The scale of the photography will then vary in the direction of the tilt from a minimum of:

$$S = \frac{f \cos (t + \frac{\theta}{2})}{H \cos \frac{\theta}{2}}$$

to a maximum of: (15)

$$S = \frac{f \cos (t - \frac{\theta}{2}}{H \cos \frac{\theta}{2}}$$

The mean value of d, however, will be zero and an approximate mean scale factor for the photography can be computed as

$$S = \frac{f \cos t}{H} \qquad (16)$$

The most significant increases in the magnitude of the scale factor of a specific photographic system can obviously be affected by an increase of the focal length or a decrease in the flight height. An additional increase may also be obtained by decreasing the angle of tilt. The latter possibility will be of minor importance, however, except in the case of extremely large tilts.

b. Base: Height Ratio

The base:height ratio, or the ratio of the air distance between camera stations and the average height of the cameras above the terrain, can be found from the relation

$$\frac{b}{H} = \tan\left(t + \frac{\theta}{2}\right) + \tan\left(t - \frac{\theta}{2}\right) + \left[\tan\left(t+\frac{\theta}{2}\right) - \tan\left(t - \frac{\theta}{2}\right)\right]\left(1 - \frac{P}{100}\right) \qquad (17)$$

where: t = tilt of the optical axis of each camera

θ = field of view of camera

P = percent of stereoscopic overlap

This relation is based on the normal configuration in which the tilts of

each of the photographs comprising a stereo pair will be of equal magnitude: one-half the convergence angle, and of opposite sign. The equation can then be written as:

$$\frac{b}{H} = \tan\left(\frac{\theta}{2} + \frac{\theta}{2}\right) + \tan\left(\frac{\theta}{2} - \frac{\theta}{2}\right) + \left[\tan\left(\frac{\theta}{2} + \frac{\theta}{2}\right) - \tan\left(\frac{\theta}{2} - \frac{\theta}{2}\right)\right]\left(1 - \frac{P}{100}\right) \tag{18}$$

where θ = convergence angle of the optical axes.

Several possibilities are evident by which the magnitude of the base :height ratio may be increased; the most effective of these being an increase in the convergence angle. Such an increase in convergence, obtained by increased angles of tilt, will, however, cause a decrease in the scale factor (Equation No. 16). Therefore, a balance must be found between these two inverse relations. The slight increase in the value $\frac{b}{H}$ derived from an increase angular field of view will be significant only in the event the angles of tilt are very small as in near vertical photography. The remaining possibility of increasing $\frac{b}{H}$ by decreasing the percent overlap is obviously undesirable.

The combinations of scale factor, base:height ratio, and resolving power required to obtain detection of very small height differentials from extreme altitudes will be determined in the following discussions for the two basic photographic systems: vertical and convergent. The vertical photography will be considered to have a minimum stereoscopic overlap of 55 percent and the convergent to have 100 percent overlap . No discussion of either parallel oblique or convergent oblique photography will be given as the geometry of these will be quite similar to that of vertical and convergent, respectively. The increase in the base:height

ratio afforded by these oblique tilts will be negated by an equal decrease in scales; thereby producing no increase in the detection of elevation changes.

4. Vertical Photography

The general expression for the scale factor and base:height ratio may be greatly simplified for this evaluation of truly vertical photography in that the tilt and convergence angles will be zero and the minimum desirable stereoscopic overlap will be 55 percent. These equations will then be:

$$S = \frac{f}{H} \tag{19}$$

$$\frac{b}{H} = 0.9 \tan \frac{\theta}{2} \tag{20}$$

The basic parallax formula (4) may now be rewritten for vertical photography as:

$$\Delta H = \frac{1}{0.9 \tan \frac{\theta}{2}} \cdot \frac{H}{f} \cdot \frac{1}{2R} \tag{21}$$

This may be further simplified through the relation of the angular field of view of the camera to the focal length and the film format (W).

$$\tan \frac{\theta}{2} = \frac{W}{2f}$$

Equation No. 21 will now be:

$$\Delta H = \frac{H}{0.9 \ W \ R} \tag{23}$$

From this equation it can be seen that the smallest detectable elevation difference will become a minimum when the variables W and R are considered at their maximums. The absence of the focal length in this equation indicates that an increased focal length will not improve the detection of terrain elevation differences. This fact is derived from the inverse relation of the focal length and field of view as shown in Equation No. 22. An increase in the scale factor obtained through an increase in the focal length will result in a proportional decrease in the base:height ratio by decreasing the angular field of view. Thus, for a given film format, the smallest detectable elevation change will be dependent on the flight height and resolving power only. This relation will be:

$$\Delta H = \frac{H}{274.32 \ WR} \tag{24}$$

where: ΔH, H and W are in feet, and

R is in lines per millimeter

The resolving power required to obtain detection of a desired ΔH from a given flight height can be determined by selecting a representative optimum value for the factor W. This optimum format will be restricted by the majority of present aerial cameras and films and by existing photogrammetric equipment to a maximum of about nine inches.

Although several photographic systems exist which will give formats up to eighteen inches, the increased dimensional instability of these larger exposures makes their use inadvisable in precision work. Figure No. 12 shows the resolution requirements for various $\Delta H/H$ combinations when using a nine-inch format. The range of resolutions hachured (up to 80 lines per millimeter) is approximately that which can be obtained by present systems.

This figure illustrates that the barest detection of six-inch elevation changes from 10,000 feet with vertical photography will require an exceptionally good photographic system, while the detection of three-inch differentials from 25,000 feet is completely out of the question. Figure No. 12 may be summarized for a practical maximum resolving power of 80 lines per millimeter as:

$$\frac{\Delta H}{H} = \frac{1}{16500} \tag{25}$$

A similar limit may be expressed for easily recognizing the elevation changes and possibly identifying their cause through vertical photography as:

$$\frac{\Delta H}{H} = \frac{1}{16500} \times 5 = \frac{1}{3300} \tag{26}$$

5. Convergent Photography

This analysis of convergent photography having an angle of

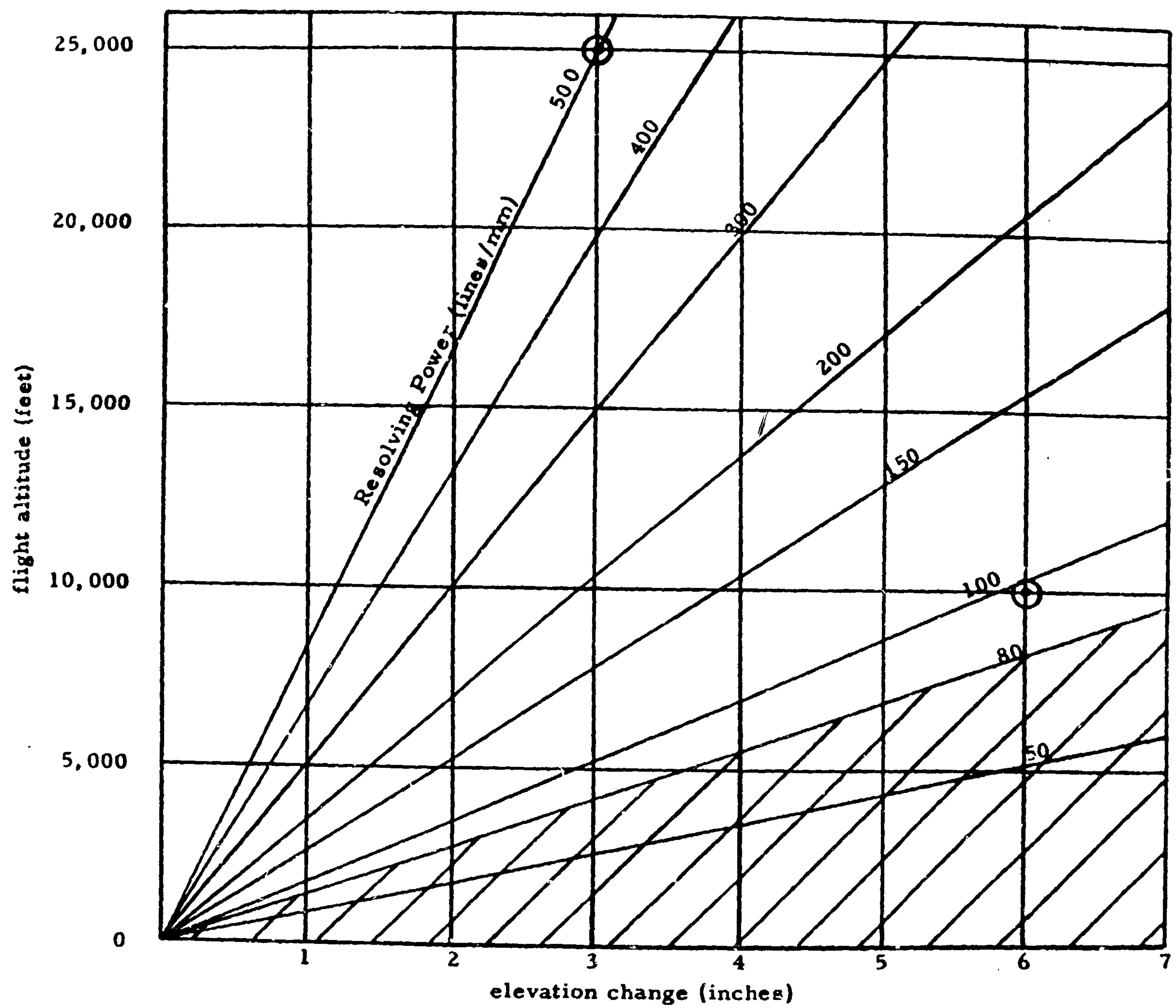

Figure 12_ REQUIREMENTS FOR VERTICAL PHOTOGRAPHY

convergence ϕ and 100 percent stereoscopic overlap will be developed in a manner similar to that used for vertical photography. In this case the expressions for the scale factor and base:height ratio will be:

$$S = \frac{f \cos \frac{\phi}{2}}{H} \tag{27}$$

$$\frac{b}{H} = \tan\left(\frac{\phi}{2} + \frac{\theta}{2}\right) + \tan\left(\frac{\phi}{2} - \frac{\theta}{2}\right) \tag{28}$$

Only minor variations will occur in the base:height ratio when the field of view of the camera is assumed to be quite small; therefore, this latter relation may be approximated by:

$$\frac{b}{H} = 2 \tan \frac{\phi}{2} \tag{29}$$

Substitution of these values into the basic parallax formula (4) will give for convergent photography:

$$\Delta H = \frac{1}{2 \tan \frac{\phi}{2}} \cdot \frac{H}{f \cos \frac{\phi}{2}} \cdot \frac{1}{2\ R} \tag{30}$$

or

$$\Delta H = \frac{H}{4\ f\ R\ \mathrm{sm}\ \frac{\phi}{2}} \tag{31}$$

When ΔH, H and f are given in feet and R in lines per millimeter, Equation 31 will become:

$$\Delta H = \frac{H}{1219.2\, f\, R\, \mathrm{sm} \frac{\phi}{2}} \tag{32}$$

The resolving power required to detect a desired ΔH from a given flight height will in this case be directly dependent on both the focal length and the angle of convergence. This dependency is illustrated in Figure 13, which shows the resolution requirements for detecting three-inch elevation changes from 25,000 feet for a range of focal lengths and convergence angles.

This figure clearly illustrates the increased precision in differential elevation detection through increased angles of convergence. The best angle of convergence for a particular application will generally be limited by the relief of the terrain to be photographed. If terrain having extreme differences in elevation is photographed with large angles of convergence, there will be large "blind spots" or areas of lower elevations which are obscured or hidden by nearby higher elevations. Where blind spots occur in either one or both of the stereoscopic photographs, no photogrammetric measurements can be made. When the measurements are to be made on relatively flat terrain, however, this restriction will have very little effect, and convergence angles as large as 60 to 90 degrees would seem feasible.

In Equation No. 30 the term $1/2R$ was described as the size of the smallest detectable detail or parallax difference in the photography and the term $H/f \cos \frac{\phi}{2}$ as the inverse of the mean scale factor. It can be seen then that the product of these terms:

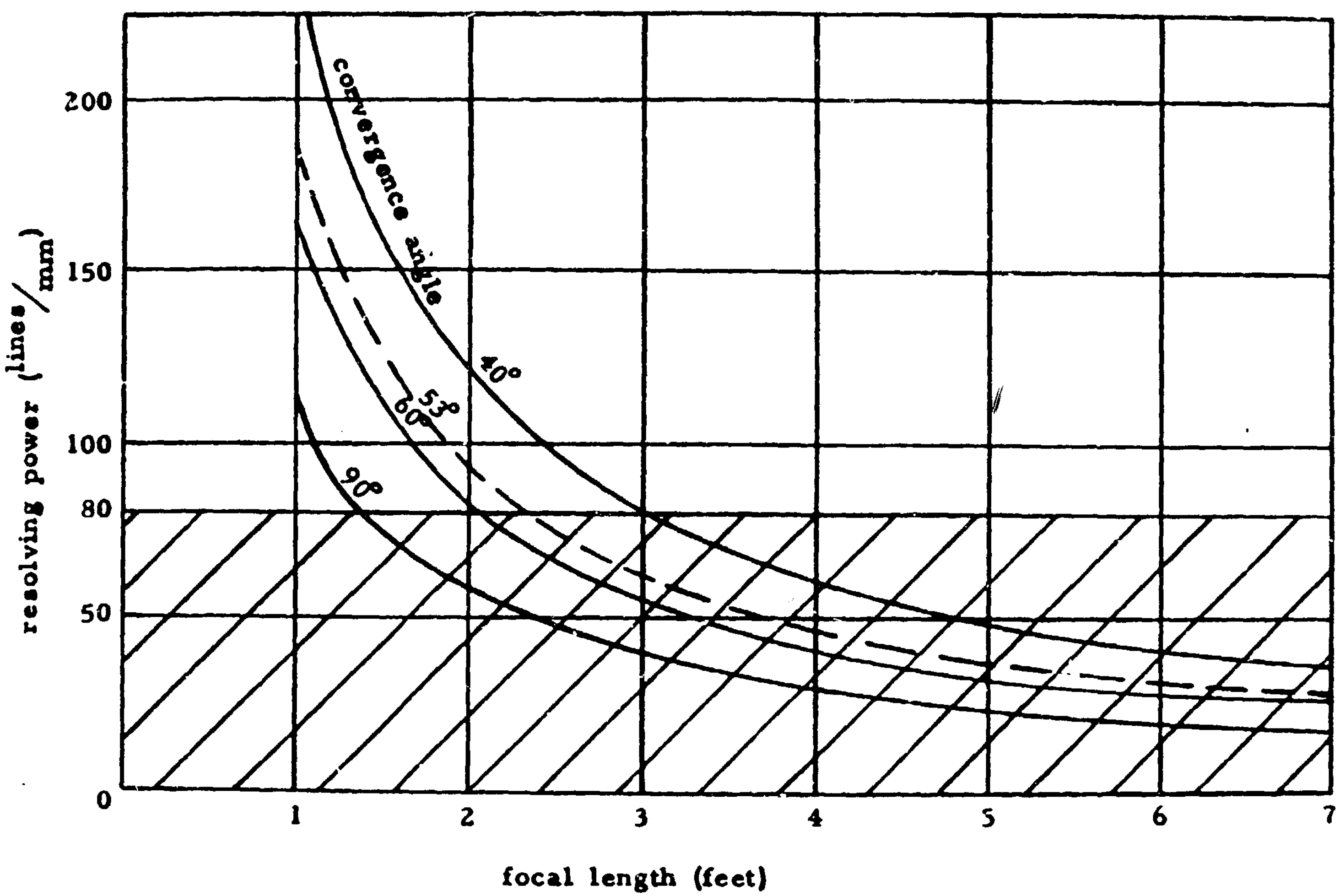

Figure 13— PHOTOGRAPHIC REQUIREMENTS FOR DETECTING THREE-INCH ELEVATION CHANGES FROM 25,000 FEET WITH CONVERGENT PHOTOGRAPHY.

$$\frac{H}{f \cos \phi \; 2} \cdot \frac{1}{2 \; R} = G \qquad (33)$$

will give the size of the smallest detectable detail or parallax difference on the ground. The relation between the smallest detectable elevation differential and the smallest detectable ground detail may now be shown as:

$$\Delta H = \frac{G}{2 \tan \frac{\phi}{2}} ,$$

or as a ratio:

$$\Delta H = \frac{1}{2 \tan \frac{\phi}{2}} \qquad (34)$$

The solution of Equation No. 34 for various angles of convergence is shown graphically in Figure 14. The slope of the curve in this figure illustrates that for a photographic system with a known resolving power:

a. A decrease in the angle of convergence will increase the interpretability of ground detail, but will decrease the detection of elevation differences. And, conversely;

b. An increase of the convergence angle will increase the detection of elevation differences while decreasing the interpretability of detail.

The interpretability of elevation differences and of their causes will, in general, be of equal importance in the photo interpretation and photogrammetric procedures. The best compromise between these

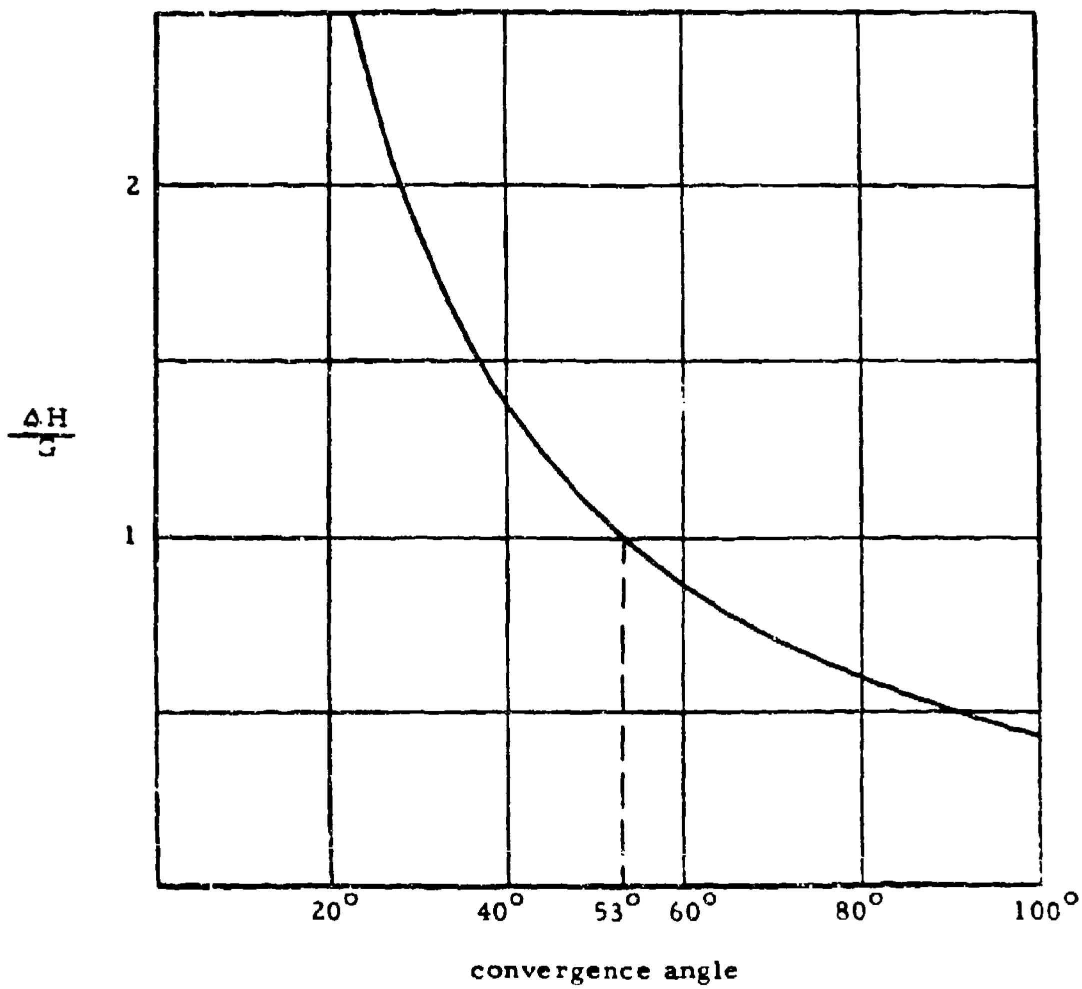

Figure 14

INTERPRETABILITY OF HORIZONTAL AND VERTICAL DETAIL

will then be the point where $G = \Delta H$, or $\frac{\Delta H}{G} = 1$. From Figure 14 this can be seen to require a convergence angle of approximately 53 degrees. Equation 33 may be simplified for this ideal convergence angle and will be:

$$\frac{\Delta H}{H} = \frac{1}{544.1\ FR} \tag{35}$$

A graphical solution of Equation 32 is also given in Figure 13. This clearly illustrates that for a practical resolving power of 80 lines per millimeter or less, the detection of three-inch elevation changes is possible for altitudes of 25,000 feet. At this particular angle of convergence the interpretability of horizontal ground detail will be equal to that of the elevations. The level of interpretability computed from Equation 35, however, is that which will afford only the barest detection of the elevation change. The requirements for easily recognizing the elevation changes and possibly identifying their causes at this angle of conv gence can be expressed as:

$$\frac{\Delta H}{H} = \frac{1}{544.1\ FR} \times 5 = \frac{1}{108.8\ FR} \tag{36}$$

At the assumed maximum resolving power of 80 lines per millimeter this will be:

$$\frac{\Delta H}{H} = \frac{1}{8704\ f} \tag{37}$$

Example solution of Equation 37 shows that an accurate analysis of three-inch elevation changes from 25,000 feet would require a focal length of over 11 feet and for six-inch changes from 10,000 feet, a focal length of less than three feet is required. The optimum flight height will be dependent, therefore, upon the maximum focal length of the camera selected.

6. Cameras

The preceding evaluation of photographic systems demonstrated the need for extremely well-stabilized, high-resolution photography taken with some degree of stereoscopic convergence. These considerations were of a very general nature and the results of the investigations apply equally well to all camera configurations. We will discuss here the three basic camera designs: framing, strip, and panoramic, and their inherent advantages and disadvantages for use in precision, high altitude photogrammetric procedures.

a. Framing Cameras

Framing cameras can be defined as those in which each photograph is exposed instantaneously over the entire format or frame. These cameras have proven to be extremely useful in photogrammetric work through the absence of any movement of either the optics or film (excepting some methods of IMC) during exposure. This stationary relation between the film and optics makes possible an accurate control

over the errors influencing the resolving power and true central perspectivity of the photography.

The theoretical resolving power of a framing camera can be established, as in any photographic system, through a knowledge of the resolution capabilities of the lens and film selected. Maintaining this resolving power under dynamic conditions, however, will require a sensitive stabilization and vibration isolation system. These stability requirements are somewhat simplified for a framing camera in that they need only apply during very short exposure times.

The framing camera acquires both an advantage and disadvantage from the narrow fields of view required of a high resolution system. The disadvantage is in the effectively reduced ground coverage obtained in each exposure. This in turn will introduce severe navigational problems in acquiring proper stereoscopic overlap between successive exposures. As previously indicated, the scale factor for convergent photographs will vary across the format as a function of the field of view. A minor advantage in high resolution systems with their narrow fields of view will be evident in that they will minimize this effect.

A definite advantage of framing cameras for use in photogrammetric work is derived from the capability for accurately determining and correcting errors due to lens distortions and dimensional changes of the film. The correction of lens distortion is facilitated through the relative stability of the film plane and the optical system. At present, the use of glass plates or reseau grids for correcting film distortions is only applicable to the type of cameras in which the entire exposure is made simultaneously.

Existing framing cameras, as well as the types to be discussed later, are somewhat limited in focal lengths. Although several extremely long focal length, high-resolution systems are under development by various agencies, the longest focal length cartographic camera which is readily available will be about 48 inches.

b. Strip Cameras

Strip or sonne cameras obtain an image of the terrain through a narrow slit in a masked film plane. The film is transported past this slit at a velocity proportional to the ground speed of the aircraft when reduced to the scale of the photography. Such a system will produce a continuous or strip photograph of the terrain. The exposure time for this type of photography is determined by the speed at which the film is transported past the slit and by the width of the slit itself; image motion compensation is implicit in the film transport speed.

These cameras have the advantage of producing a continually high on-axis resolving power along the centerline of each strip. They have, however, the same disadvantages as the framing camera in requiring very narrow fields of view to maintain a high resolving power across the strip. Additional disadvantages are presented by the lack of any means for detecting dimensional changes in the film, and by the severe stabilization and vibration isolation requirement during the relatively long exposure for each strip. As the shutter remains open during the exposure of each strip, this will not be a source of resolution loss. It is evident, however, that the film transport motor must operate contin-

uously and will be a continual source of vibration. This continual movement of the film also eliminates any possible application of either glass plates or reseau systems for eliminating film distortion.

Strip cameras are extremely useful in obtaining low altitude photography from high speed aircraft. These systems will have a great disadvantage at greater altitudes in that for reasonable exposure times an exceedingly small slit or high airspeed is required. They are useful in convergent systems, however, because the field of view in the direction of tilt will be reduced to that permitted by the width of the exposing slit. This will effectively produce a constant photographic scale over the entire strip.

Strip cameras are usually modifications of framing cameras and are limited to approximately the same focal lengths.

c. Panoramic Cameras

Panoramic cameras are essentially a combination of both the framing camera and the strip camera. The photography in this case is obtained one frame at a time, but the exposure is made through a slit which traverses across the film. The movement is generally accomplished by rotating the lens about its nodal point. Through a mechanical connection to this rotating lens, the imaging slit is made to follow the optical axis of the lens across a curved film plane. The radius of curvature of the film plane is equal to the focal length of the objective. This rotation or scanning is usually performed in a direction normal to the flight path and image motion compensation is introduced by a translation of

of the lens along the flight path. The exposure time for a portion of each frame will be determined by the speed of scan and the width of the slit. The total exposure time for each frame will then equal the total scan time. These relatively long total exposure times will introduce severe stabilization problems similar to those for strip photography.

Panoramic cameras have the advantage of the strip cameras' continual on-axis resolution while at the same time effectively increasing the field of view in the direction of scan. They will also have the same disadvantage in that no possibility exists for correcting dimensional changes of the film. The use of either glass plates or reseau grids on a curved film plane will be impractical, if not impossible.

Panoramic photography will have a variable scale factor in both the direction of tilt of the optical axis, as controlled by the angular field of view of the lens, and in the direction of scan, as controlled by the angular field of the scan. Because of the continual motion of the optical system from side to side, the physical size of these systems are presently limited to 12 and 24-inch focal length. Larger systems are being designed and developed, but are not presently available.

7. Summary

High altitude measurements of extremely small terrain elevation changes were shown to require photography taken with some degree of convergence. An ideal convergence angle of 53 degrees was developed. This convergence will provide an approximately equal interpretation of both horizontal and vertical terrain detail. A relation between the

photographic parameters was given which would afford a level of interpretability at which the elevation changes would be easily recognized and their causes identified. This relation is:

$$\frac{\Delta H}{H} = \frac{1}{108.8\, fR} \qquad \left[\text{see } (36)\right]$$

As the size of the smallest elevation change for which this level of interpretability is possible is obviously dependent on the photo scale and the system resolving power, indications were given of the optimum values of these factors.

The maximum resolving power was given as approximately 80 lines per millimeter. This is not a definitive value, but based on the capabilities of present systems: This is a practical assumption. The relation above may be rewritten for this assumed resolving power as:

$$\frac{\Delta H}{H} = \frac{1}{8704\, f} \qquad \left[\text{see } (37)\right]$$

The optimum focal length and, therefore, the flight height will be determined by the selection of an approximate camera. From the analysis of the various camera designs, it is proposed that the conventional framing camera be used for this application. Although a strip camera will have a more consistent photo scale, and a panoramic camera, a larger lateral field of view, the increased stability and control of the framing camera is deemed more important. The maximum focal length of 48-inches, the relation above will reduce to approximately:

$$\frac{\Delta H}{H} = \frac{1}{35000} \qquad (38)$$

A reliable analysis of three-inch terrain elevation changes will then require a flight height of about 8750 feet, and for six-inch changes, a flight height of 17,500 feet.

In the event that the photographic requirements as specified above are maintained, elevation changes of three and six inches will be easily analyzed through stereoscopic photo interpretation procedures. These techniques are well known and no departures from present procedures will be necessary for this investigation. The requirement for convergent photography, however, may introduce minor difficulties in stereoscopic vision by direct viewing, due to the scale variations in this type of photography. These difficulties are illustrated in Figure 15 where it can be seen that the variations in scale cause not only a difference in size of the objects but also a rotational position change.

The extent of these problems will be dependent on the magnitude of the angle of convergence and the angular field of view of the photographic system. These problems, however, when recognized and evaluated may be easily corrected.

It was shown that the scale of a tilted photograph will vary from:

$$S_{min} = \frac{f \cos\left(\frac{\phi}{2} + \frac{\theta}{2}\right)}{H \cos\frac{\theta}{2}} \qquad \left[\text{see } (15)\right]$$

to:

$$S_{max} = \frac{f \cos\left(\frac{\phi}{2} - \frac{\theta}{2}\right)}{H \cos\frac{\theta}{2}}$$

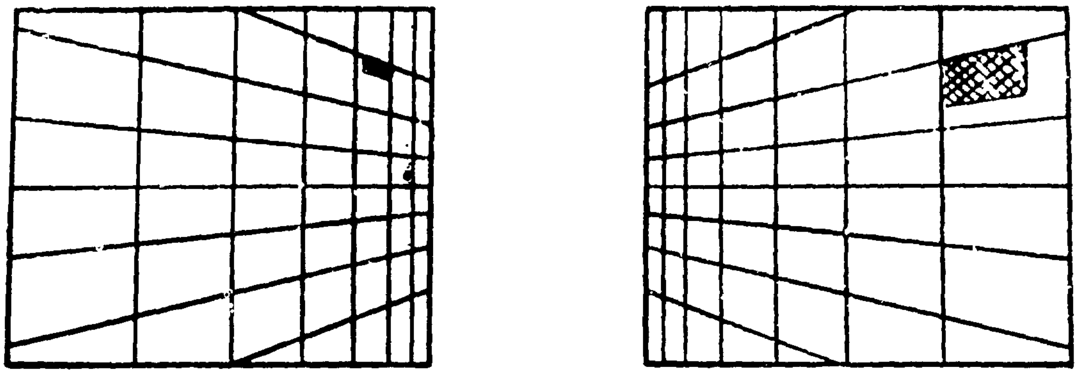

Figure 15

GEOMETRY OF CONVERGENT PHOTOGRAPHY

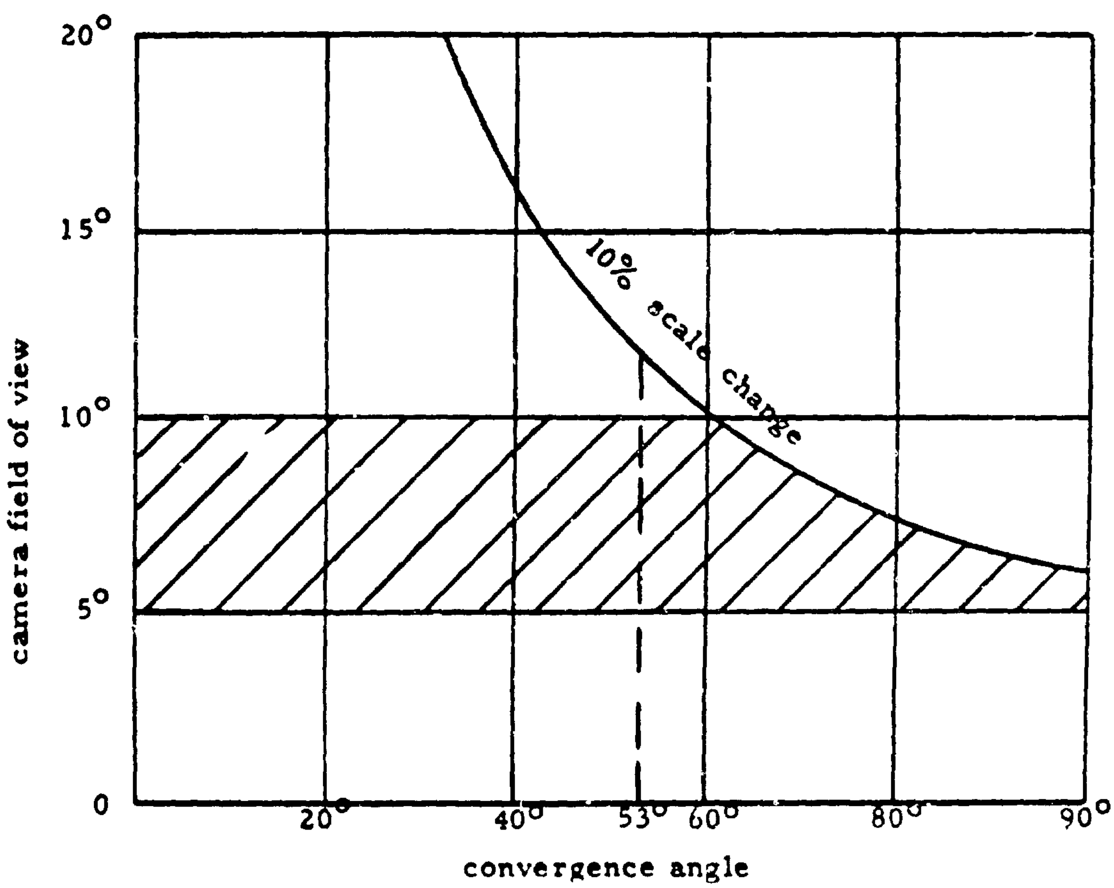

Figure 16

SCALE CHANGE IN CONVERGENT PHOTOGRAPHY

where ϕ and θ are the convergence angle and angular field of view respectively. When two such photographs are taken with tilts of equal magnitude but of opposite sign to obtain a stereoscopic overlap of 100 percent, it can be visualized that the area photographed at the maximum scale of one photography will correspond to the area of minimum scale on the other. Thus, the maximum variation in scale between the images in each of the two photographs may be computed as $S_{max} - S_{min}$ or:

$$\Delta S\% = \frac{f \; 2 \sin\frac{\phi}{2} \; . \; \sin\frac{\phi}{2}}{H \cos\frac{\theta}{2}} \qquad (39)$$

This scale difference may be given as a percentage of the maximum scale by the expression:

$$\Delta S\% = \frac{2 \sin\frac{\phi}{2} \; \sin\frac{\theta}{2}}{\cos\frac{\phi}{2} \; \cos\frac{\theta}{2} + \sin\frac{\phi}{2} \; \sin\frac{\theta}{2}} \times 100 = \frac{200}{\cot\frac{\phi}{2} \; \cot\frac{\theta}{2} + 1} \qquad (40)$$

Throught experience it has been found that proper stereoscopic vision can only be obtained if the scales of corresponding images vary by no more than about 10 percent. Substituting this maximum $\Delta S\%$ in equation 40 will give

$$\cot\frac{\phi}{2} \quad \cot\frac{\theta}{2} = 19 \qquad (41)$$

A graphical solution of this equation is shown in Figure 16. This figure illustrates the maximum combinations of convergence angle and angular

field of view to obtain immediate stereoscopic vision. The term immediate is used here to indicate the possibility of an intermediate rectification process in cases where these maximums are exceeded. Such a rectification step will alleviate the scale problem in all cases, but the subsequent loss of resolution makes this step advisable only when absolutely necessary. The high resolution requirements for analyzing small elevation changes will limit the field of view of the cameras to such an extent (approximately 5 - 10 degree) that the possibility of exceeding the maximums indicated in Figure 16 will be very remote.

Convergent photography was also shown to introduce a rotational change in the positions of objects. This change can be seen to be zero along the flight line and increase with the distance of the objects from this line. It is evident, therefore, that when scanning a pair of convergent photographs, proper stereoscopic vision can be maintained only if these rotational changes are corrected by rotations of the photographs. Although a rotation of the photographs will not drastically effect the photointerpretation procedure, it will be shown in the following section that such a rotation will be impossible when making photogrammetric measurements. These rotational position changes can also be eliminated by a rectification of the photography, but only with a corresponding loss in resolution.

E. PHOTOGRAMMETRIC ANALYSIS

1. Error Considerations

The photogrammetric measurement of a terrain elevation change will be found as the difference between the elevation measurements of two individual points. To determine the expected precision of such a measurement will require a complete evaluation of the errors affecting each of the individual elevation measurements. The variety of errors which will detract from the precision of this photogrammetric operation were briefly discussed in Section C. These are listed again below. The effects of these errors on the precision of the mensuration technique will fall into either of two main categories. These are:

a. Those errors which will have an equal influence on the precision of all elevation measurements in the stereo model.

(1) Instrumental and operator measuring errors

(2) Errors in determining photo scale or model scale

b. Those errors which will influence the precision of the elevation measurements as a function of the position of the points in the model.

(1) Model deformations due to errors in the relative orientation and model leveling

(2) Lens distortions

(3) Dimensional changes of the film

(4) Earth curvature

(5) Atmospheric refraction

A general evaluation of the effects of these errors on the measurement of any elevation change in the model would obviously require that all possible combinations of individual point pairs be considered. This evaluation, however, may be greatly simplified for special applications in which the relative positions of the individual points will be known or can be assumed.

Through a consideration of the terrain elevation changes which will be detrimental to aircraft landing operations, it may reasonably be assumed that changes of the magnitude searched for in this investigation (approximately three to six inches) must occur over very short horizontal distances to be significant. These may be visualized as rather abrupt or rapid changes. Elevation changes of this size occurring over longer distances will result only in a gradual slope of the terrain and should not greatly hamper aircraft operations. Therefore, in this specialized investigation, we shall consider the elevation changes for which the greatest measuring precision is required to be randomly distributed throughout the model and to occur primarily between two closely adjoining points. As the separation between the individual points increases, the influence of the corresponding elevation change on the landing operations will decrease. Consequently, a slight decrease in the precision of the measurements will be permissible.

An evaluation of the influences of the errors listed above is greatly simplified by this assumption. This is particularly true of the errors in group two. These errors will be rather systematic,

and the magnitude and the sign of their contribution to the elevation measurement of a point will be dependent on the location of the point in the model. It can be seen that the elevation measurements of two points within close proximity of one another will each receive errors of approximately equal magnitude and sign from these sources. The resulting error in the elevation difference between two such points, therefore, will be negligible. These errors will be of importance in this investigation only in so far as they will determine the rate at which the precision of the elevation differences will decrease as the separation between the individual points increases.

The remaining errors (group one) are those which will have an approximately equal influence on the elevation measurements of all points in the model. The instrumental and operation errors will primarily be accidental, both in magnitude and in direction, and their influence on a particular measurement is not easily predictable. The errors in a series of such measurements, however, will conform to an approximate Gaussian distribution and the magnitude of the most probable error in a single measurement can be derived statistically. In the following investigation this probability will be expressed as a root mean-square error (M). This error influence may be considered equal and independent for each elevation measurement in the model (M_h) regardless of the point position. The elevation measurements of two closely adjoining points as well as two widely separated points will each receive a similar mean-square error, and the resultant error in the computed elevation difference can be expressed as:

$$M_{\Delta H}^2 = M_{h_1}^2 + M_{h_2}^2$$

or:

$$M_{\Delta H}^2 = 2\ M_h^2 \quad \text{where: } M_{h_1} = M_{h_2} \tag{42}$$

From these discussions, it can be seen that the primary sources of error in the measurement of elevation differences between two closely adjoining points will be the instrument, operator and scale determination. The following discussions of photogrammetric techniques and equipment will be based on the influence of these errors. Indications will also be given of the effects of the systematic errors when the elevation changes are measured over larger horizontal distances.

As indicated above, the precision of a photogrammetric technique can be expressed by its mean-square-error in the measurement of elevation changes ($M_{\Delta H}$). This is more commonly expressed as the ratio of the measuring accuracy to the flight height $\frac{M_{\Delta H}}{H}$. It is important, therefore, in the development of a photogrammetric system for a particular application that the accuracy requirement be stated. As this requirement has not been established for this investigation, an example value will be assumed. Based on the sizes of the elevation changes to be measured (three to six inches) it will be assumed that the minimum accuracies of the photogrammetric measurements must be $M_{\Delta H} = 1/2$ inch and 1 inch, respectively. Expressed as a fraction of the required flight heights developed in the proceding section, the measuring accuracies will be:

$$\frac{M_{\Delta H}}{H} = \frac{1}{210,000} \tag{43}$$

2. Specialized Measurements

The factors which will influence the precision of the measurements of abrupt elevation differences were given as: 1) the precision of the instrument and operator, and 2) the precision with which the scale of photography or model scale can be determined. The relations between these influences and the final measuring precision are derived below.

a. Equipment

There are two main classes of equipment capable of approaching the precision searched for in this investigation. These are: the more precise stereoplotting instruments utilizing analogue solutions, and the stereocomparator type equipment, which in connection with electronic computers, developed purely analytical solutions.

(1) Stereoplotters

Precision stereoplotting instruments obtain measurements of terrain elevation differences directly from the stereoscopic, visual model of the terrain. This model is formed by a proper relative and absolute orientation of the optical or mechanical projections

of a pair of stereoscopic photographs. The relation between the elevation differences measured in such a model (Δh) and the corresponding differences in the terrain was derived in Section B to be:

$$\Delta H = \frac{H}{h} \Delta h \qquad \left[Sec(6) \right]$$

where h is the vertical projection distance of the model.

In this type of solution the Δh value measured in the model is found as the difference between two individual point elevation measurements (h_1 and h_2). Thus:

$$\Delta H = \frac{H}{h} (h_1 - h_2) \qquad (44)$$

The instrumental errors which will be evident in this computed value will be introduced by errors in these individual elevation measurements The errors in these measurements may be considered equal in magnitude and entirely independent of one another. Therefore, a general law of error propagation may be used to develop a root-mean-square error expression for the final elevation difference in the form:

$$M_{\Delta H}^2 = \frac{2H^2}{h^2} M_h^2 \qquad (45)$$

or:

$$\frac{M_{\Delta H}}{H} = \sqrt{\frac{2}{h}} \quad M_h \tag{45}$$

Equation 45 may be used to find both the precision of the model elevation measurements (M_h) and the projection distance required of this type of instrument to produce a given accuracy in the measurement of terrain elevation changes from a selected altitude. The computed measuring accuracies will apply to the measurement of all terrain elevation changes regardless of their size. The size of the changes will have effect only when the visual perception of the operator is also considered.

As stated in the derivation of equation 6, this relation is valid only in the event that the principal distance of the projection systems are equal to the focal length of the photographic camera. The precision stereo plotting instruments used in conventional photogrammetric mapping and engineering work have unfortunately been developed for use only with the more common types of cartographic photography. Each of these instruments is capable of accommodating photography taken within a very limited range of focal lengths. At present, the maximum focal length which can be used with this type of equipment is about twelve inches. This is true also of the more recently developed U.S. Army "Halcon" plotter which was designed specifically for use with high altitude convergent photography.

This type of equipment also has a very limited range of projection distances and measuring accuracies. This can be

seen through a comparison of the two classes of projection equipment. What are normally referred to as the second-order instruments are those which are used in conventional topographic mapping. This class will include such plotters as the Kelsh and the Balplex. These, in general, will have a maximum projection distance of about 760 millimeters and a measuring accuracy of $M_h = 0.05 - 0.10$ millimeters. Under optimum conditions, this would produce a $\frac{M_{\Delta H}}{H}$ value of about only $\frac{1}{10860}$. The Halcon system has increased this accuracy, through a longer projection distance, to a value of about $\frac{1}{20,000}$. If three- or six-inch elevation changes are to be measured with any reliability, however, a system should be developed which will give a $\frac{M\Delta H}{H}$ of at least $\frac{1}{210,000}$.

The more precise class of projection instruments is normally referred to as the first-order, or universal instruments. These names are derived from both their increased precision and their adaptability for aerial triangulation. This class will include such plotters as the Zeiss Stereoplanigraph and the Wild Autograph. These instruments will be limited to a projection distance of approximately 600 millimeters, but will have a measuring precision of the order of 0.01 millimeters. This would indicate a $\frac{M\Delta H}{H}$ value of about $\frac{1}{60,000}$.

The use of either class of projection equipment with photography taken with focal length in excess of one foot will require modified projection systems; and to obtain measurements of

greater accuracy than those discussed above will require either an increase of the projection distances or an increase in the instrumental measuring precision.

(2) Stereo Comparators

The stereo comparator type instruments utilize a direct viewing system by which the stereoscopic parallaxes and the parallax differences are measured in the plane of the photographs. Following a correction of these measurements through the relative and absolute orientation procedures, these values may be related to their representative terrain elevation changes by equation 4. This relation was developed for convergent photography to be:

$$\Delta H = \frac{H}{2f \sin \frac{\phi}{2}} \Delta P \qquad \text{[See (30)]}$$

In this type of solution, the parallax difference between two points is found as the difference between the individual parallax measurements for the two points $(P_1 - P_2)$.

Thus:

$$\Delta H = \frac{H}{2f \sin \frac{\phi}{2}} (P_1 - P_2) \qquad (46)$$

These parallaxes, in turn, will be derived as the difference between the positions of the common images in each photo as measured along the common X coordinate axis of the mensuration equipment (Figure 6)

The parallax for Point One will then be $P_1 = X_{11} - X_{12}$, where X_{11} is in the position of Point One in Photograph One and X_{12} is the position of this same point in Photograph Two.

$$\Delta H = \frac{H}{2f \sin \frac{\phi}{2}} \left[(X_{11} - X_{12}) - (X_{21} - X_{22}) \right] \tag{47}$$

The instrumental errors affecting the determination of the parallax differences, and consequently the determination of elevation differences, are introduced by errors in the individual point measurements. These errors will be of equal magnitude and entirely independent of one another, and an error propagation similar to that used in the preceding section will develop an error equation in the form:

$$M \Delta H = \frac{H}{f \sin \frac{\phi}{2}} \quad M_x \tag{48}$$

For the convergence angle of 53 degrees and the focal length of four feet developed in the previous section, this equation will reduce to:

$$\frac{M \Delta H}{H} = \frac{Mx}{545.98} \tag{49}$$

where:

Mx is in millimeters

The accuracy of the more precise stereo comparators, as those of Wild, Zeiss, and Nistri, will be more or less the same. Through a procedure of repetitive measurements for each point, this will be approximately 0.002 millimeters. The accuracy of the final terrain elevation differences for this system will then be approximately:

$$\frac{M_{\Delta H}}{H} = \frac{1}{270,000} \tag{50}$$

The discussion of the photographic interpretation of convergent photography indicated the difficulties in stereoscopic vision caused by the variable scale factor and rotational relation between image points. Similar difficulties will occur in viewing convergent photography on a stereo comparator. In comparator measurements, the positions of the photographs must be kept constant; therefore, the rotational relation between conjugate image points cannot be corrected by rotating the photographs. The loss of resolution and distortions introduced through a rectification process are again undesirable. The best solution is to have both the scale and the rotations of images corrected by optical or mechanical changes in the observing system. Corrections of this sort may be introduced by pancratic or variable magnification systems and image inverter systems, with no change in the measuring precision of the equipment. Although such systems are used in other photogrammetric instruments, no stereo comparators are as yet equipped

with these or any other means of handling convergent photography.

At present, there are no photogrammetic instruments, either analogue plotters or stereo comparators, capable of handling extremely long focal length convergent photography. A comparison of the modifications required for adaptation of each type of instrument indicates the desirability of using a stereo comparator for the proposed measurements. This selection is further substantiated by the flexibility of this equipment for use with any focal length photography and its greater precision.

Equation 50 would indicate that for the proposed systems the stereo comparator equipment is sufficiently accurate to produce the desired accuracies in the measurement of abrupt elevation changes. However, this is indicative only of the equipment reliability, and even for these specialized measurements, the accuracy can be degraded by limitations of the operator's visual acuity and by errors in the determination of the photo scale.

b. Operator

The limit of the operator's depth perception was given in Section D in terms of the smallest detectable parallax as:

$$\Delta p_{min} = \frac{1}{2R} \qquad (51)$$

It is important to note, however, that the visual acuity of the human eye, at normal viewing distances, will not be as great as the resolving power of the photography. Therefore, in order for the information content of high resolution photography to be fully utilized, this photography must be viewed under large magnifications. To acquire the perception indicated in equation 51, using photography with resolving powers of the order of 80 lines per millimeter, will require enlargements of at least 10X and possibly as high as 20X. For precision work, such enlargements should be obtained optically through the viewing systems rather than photographically. The additional photographic procedures required to enlarge the photographs themselves will introduce losses in the resolving power as well as additional lens distortions and film shrinkages.

The required enlargements can be obtained easily for procedures in which the observing systems are aided by oculars. The proper selection of magnifying oculars for the stereoscopes used in photo interpretation and for the stereo comparators will provide the desired enlargement. This will be true also of the first-order plotting instruments in which oculars are used. In the second-order plotting instruments, however, the stereo model is viewed with the unaided eye and the only magnification available is that provided by the ratio of the projection distance to the principal distance of the projectors $(\frac{h}{c})$. To fully utilize the resolving power of the photography in these systems would require projection distances in excess of ten times the focal length of the camera.

The visual perception expressed by equation may be assumed to be approximately the mean-square-error in the detection of small elevation changes under sufficient magnification. The effect this will have on the stereo comparator measurements is shown below.

(1) Stereo Comparator Measurements

The precision of the stereo comparator measurements was expressed as:

$$M_{\Delta H} = \frac{\sqrt{2}H}{2f \sin \frac{\phi}{2}} \qquad M_P \qquad \left[\text{See (46)}\right]$$

where Mp is the precision of each of two parallax measurements. Each of these parallax measurements will include the precision of operator's ability to place the floating mark on each point in the model $\left(\frac{1}{2R}\right)$ and that of the coordinate values of the marks in each photograph:

$$\left(\sqrt{M^2_{x_1} + M_{x_2}^2} = \sqrt{2}M_x\right).$$

Equation may be rewritten then as:

$$\frac{M_{\Delta H}}{H} = \frac{\sqrt{2}}{2f \sin \frac{\phi}{2}} \sqrt{2M_X^2 + \left(\frac{1}{2R}\right)^2} \qquad (52)$$

This will simplify for an $Mx = 0.002$ millimeters and a resolving power of 80 lines per millimeter to:

$$\frac{M \Delta H}{H} = \frac{\sqrt{2}}{2f \sin \frac{\phi}{2}} (0.007) \qquad (53)$$

which for the example system will be:

$$\frac{1}{}\ \frac{\Delta H}{H} = \frac{1}{110,000} \qquad (54)$$

The loss in measuring accuracy due to the limited perception of the observer can be seen readily through a comparison of equations 50 and 54. Also, the accuracy expressed by the equation 50 will be seen to be lower than the desired $\frac{1}{210,000}$ by a factor of two. The possibilities for improving this situation are:

(1.) Increased resolution

(2.) Increased focal length

(3.) Decreased flight height

However, with such a vast difference between the capability of the equipment and that of the operator, any attempt to increase the measuring precision of the stereo comparators would be of very little value.

Maintaining the assumption that the optimum focal length and resolving power will be four feet and 80 lines per millimeter, respectively, many combinations of flight heights and measuring

accuracies are possible. For example, to obtain the desired measuring accuracy of $M \Delta H = 1$ inch with this system will necessitate a decrease in the flight height from 17,500 feet to about 9,000 feet. Similar solutions may be developed for any other focal lengths, resolving powers, and measuring accuracies desired.

c. <u>Scale</u>

The scale of the photographs can be determined either from the scale factor, for which convergent photography is $\frac{f \cos \frac{\phi}{2}}{H}$, or from a comparison of a known distance in the terrain to the same distance on the photographs. We shall consider here only the more general situation in which no ground control information will be available.

The relation between the precision of the scale determination from flight height and focal length information and the resultant precision in the measurement of terrain elevation changes can be found through an error analysis of equation 4. This equation will develop for convergent photograph to approximately:

$$\Delta H = \frac{H}{2f \sin \frac{\phi}{2}} \Delta P \qquad \left[\text{See}(30)\right]$$

Applying the general law of error propagation to the equation will give:

$$M_{\Delta H}^{2} = \frac{H^2}{4f^2 \sin^2 \frac{\phi}{2}} M_{\Delta P}^{2} + \frac{\Delta H^2}{H^2} M_H^{2} + \frac{\Delta H^2}{f^2} M_f^{2} + \frac{\Delta H^2}{\tan^2 \frac{\phi}{2}} M_{\frac{\phi}{2}}^{2} \tag{55}$$

The first term on the right side of this relation is the error contribution of the mensuration equipment and the operator which was discussed previously. The remaining terms are those which will influence the scale of the photography and thus, the scale of the measurements.

By visually comparing the coefficients of the four terms in the equation, it can be seen that when very small elevation changes are measured from great heights, relatively large errors in the scale terms will have only a minor influence on the measuring accuracy. This can be illustrated most easily by introducing typical values for M_H, M_f, and $M_{\frac{\phi}{2}}$.

In the preceding analysis of the proposed system, the first term was found to be approximately $\frac{1}{110,000}$, which for the measurement of a six-inch elevation change from 17,500 feet, would be about $M_{\Delta H} = 2$ inches. Let us assume the following typical values for the scale errors:

$M_H = 10$ feet $= 120$ inches; based on the capability of radar altimetry.

$M_f = 0.01$ millimeters , 0.0004 inch; based on conventional camera calibration techniques, and:

$M_{\frac{\phi}{2}} = 1$ degree of arc $= 0.017$ rad.; based on the stability of a moderately good camera mount.

Substituting these example values into equation 55, the resultant error in the measurement of six-inch elevation changes from 17,500 feet will be approximately:

$$M_{\Delta H}^{\,2} = (2\text{ in.})^2 + \left(\frac{6}{17500} \times 10\text{ in.}\right)^2 + \left(\frac{\frac{1}{2}}{4} \times 0.0004\text{ in.}\right)^2$$

$$+ \left(\frac{6}{0.5} \times 0.017\text{ in.}\right)^2$$

$$M_{\Delta H} = 2.01\text{ in.} \qquad (56)$$

It can be seen from this example that present controls over the scale errors are sufficient to eliminate any significant influence of these errors on the measurements of extremely small elevation changes. This will be true of both abrupt changes and those accurring at greater horizontal distances.

3. General Measurements

In the preceding discussion, only the contributions of those errors which have an equal influence on the measurements of any and all elevation changes were evaluated. By considering the specialized requirements of the proposed system, i.e., the highest accuracy will be required for rather abrupt elevation changes, the influences of those errors which will only have significant contributions to measurements over larger horizontal

distances were neglected. The measuring accuracy developed under this assumption is approximately the maximum attainable by the example equipment and photography used. This maximum accuracy will be degraded, however, as the separation between the points increases. As undoubtedly, in the course of the operation, some measurements of gradually sloping terrains will be desirable, the following discussions of the additional error sources will give an indication of the loss in precision encountered in this type of measurement.

a. Lens and Film Distortions

The source and means of measuring lens distortions was discussed in Section C. We refer here specifically to radial distortions. Any lens showing significant tangential distortions should be discarded. Although the radial distortions will be somewhat systematic with respect to the angular distance from the optical axis, the residual errors in correcting these distortions will be primarily accidental and will have an equal influence on the measurement of all points. Through repetitive measurements on conventional goniometers, or through star calibrations this error may be approximately $M_d = 0.005$ millimeters.

The error in correcting lens distortions would theoretically influence the coordinate measurement of each point, and the resulting influence on the final accuracy of the terrain elevation changes could be expressed as

$$\frac{M_{\Delta H}}{H} = \frac{\sqrt{2}}{2f \sin \frac{\theta}{2}} \sqrt{2 M_d{}^2} \qquad (57)$$

However, for convergent photography, taken with a very narrow field of view and 100 percent overlap, common image points will be imaged in approximately identical positions on each of the photographs and will, therefore, receive distortions of approximately equal magnitude and sign. The resultant error in the parallax measurement between two such points will then be negligible. Similarly, the influence on the measurement of parallax differences will be negligible. The small differences in scale between common image points and the inability to obtain the required precision in stereoscopic overlap, however, will make such an assumption inaccurate. On the other hand, the relatively slow rate of change of the distortion would indicate that for small errors in overlap and scale, the inaccuracy of the previous assumption would introduce errors much smaller than the M_d given above. A more accurate relation may then be approximately:

$$\frac{M_{\Delta H}}{H} = \frac{\sqrt{2}}{2f \sin \frac{\theta}{2}} M_d \qquad (58)$$

The film distortions caused by dimentional changes of the emulsion and its base will be fairly systematic in each exposure, but will vary from one exposure to the next. The errors in correct-

ing these changes (M_f) will, therefore, influence the coordinate measurement of each point, and the resulting influence on the final measurements of terrain elevation changes will be:

$$\frac{M_{\Delta H}}{H} = \frac{\sqrt{2}}{2f\sin\frac{\theta}{2}} \sqrt{2M_f^2} \qquad (59)$$

Through the use of glass plate emulsion supports, these errors may effectively be eliminated, while the use of film bases and reseau grids may result in a $M_f = 0.003$ millimeters.

The resultant influence of these two error sources, together with the instrument and operator accuracies, can be found through equation 52. Substituting the lens and film distortions in that equation will give:

$$\frac{MH}{H} = \frac{\sqrt{2}}{2f\sin\frac{\theta}{2}} \sqrt{2M_x^2 + \left(\frac{1}{2R}\right)^2 + M_d^2 + 2M_f^2} \qquad (60)$$

Under the assumptions that:

$M_x = 0.002$ mm

$\frac{1}{R} = 80$ lines/mm

$M_d = 0.005$ mm

$M_f = 0$ (glass plate) .

$M_f = 0.003$ mm (film)

$f = 4$ feet

$\theta = 53$ degrees

equation 60 will become

$$\frac{M_{\Delta H}}{H} = \frac{1}{80,000} \quad \text{for film supports} \tag{61a}$$

and

$$\frac{M_{\Delta H}}{H} = \frac{1}{90,000} \quad \text{for glass plate supports} \tag{61b}$$

For the measurement of six-inch elevation changes from 17,500 feet, equations 61a and 61b would both be approximately $M_{\Delta H} = 2.5$ inches. The loss in precision due to the lens and film distortions can be seen by comparing the equations above to equation 54.

b. Model Deformations

The errors resulting from an inaccurate relative orientation of the photography, and those introduced by atmospheric refraction, earth curvature, and model leveling, will cause elevation deformations of the stereoscopic model, and consequently, errors in elevation measurements. The elevation error introduced into each point in the model by these deformations is a function of the position of that point in the model. A general expression for the probable error at any one point in the model therefore, cannot be easily derived. However, in this discussion we will derive the general shape of the deformed model and thereby indicate the maximum elevation error which will occur at any one point, and the maximum error in the elevation difference between any

two points.

In order to determine the size of the stereo model and its ground coverage, the following discussions will refer to a photographic system with a five-degree field of view. This value is approximately that which will be dictated by the required high-resolution system. The coordinate system to be used is that shown in Figure 6, with the origin of the model coordinates at the nadir of the left-hand photograph (Photograph 1). The dimensions of the stereo model and the coordinates of selected points are shown in Figure 16a. The term h in this figure will be the flight height of the aircraft when the coordinates are desired at ground scale. In stereocomparator work in which the mathematical stereo model will be at photoscale, the h will be the focal length of the camera.

(1) Relative Orientation

In practice, the relative orientation is performed by computing the corrections to the orientation elements or freedoms of each camera by the method of least-squares, from the measurements of the small vertical parallaxes which remain in selected orientation points after a preliminary empirical orientation. For an arbitrary point in the model, a general formula for the correction of the elements of the relative orientation of convergent photographs will be:

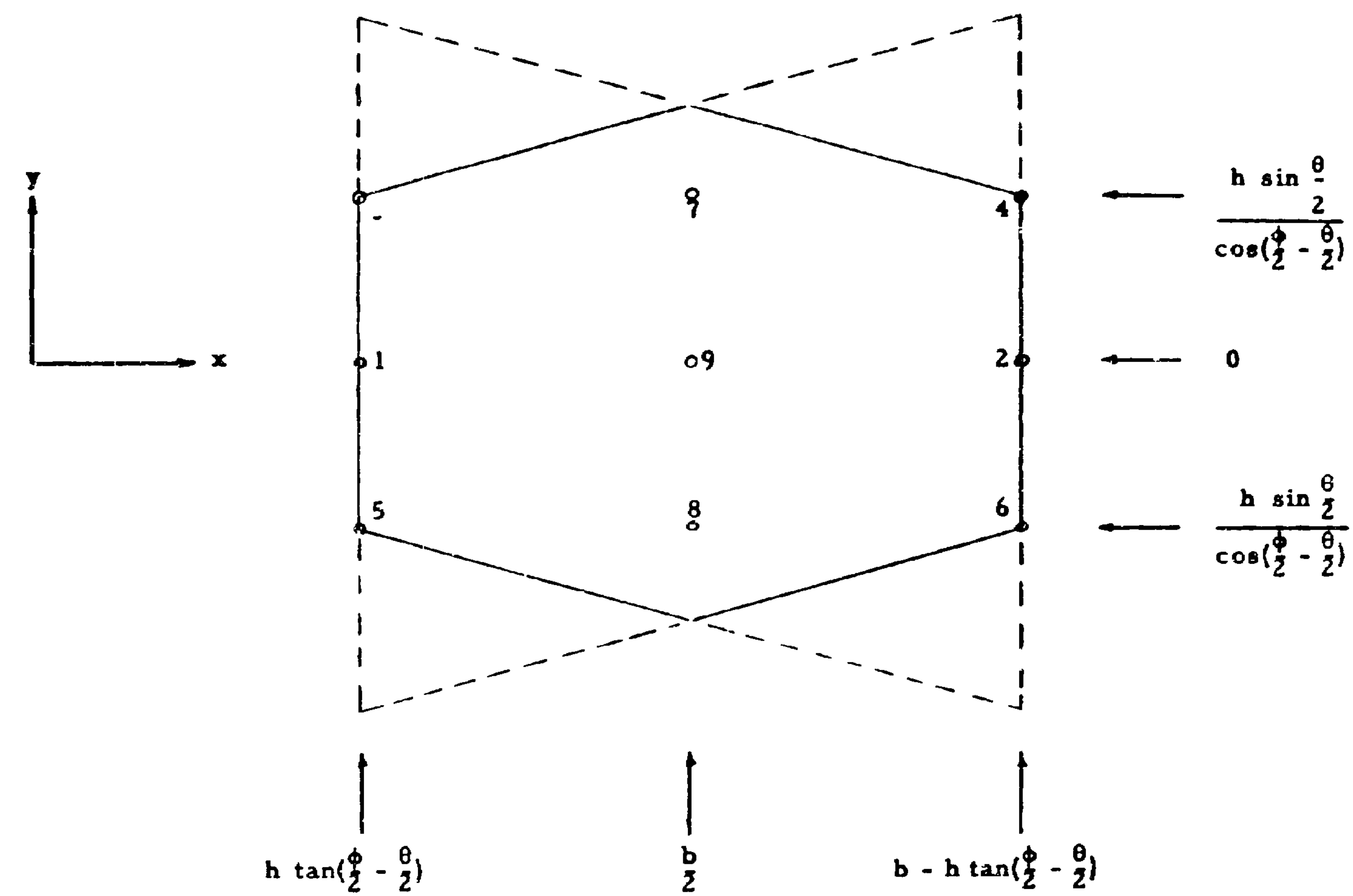

Figure 16a_ COORDINATES AND DIMENSIONS OF CONVERGENT STEREOSCOPIC MODEL

COEFFICIENTS

Pt.	x	y	dK_1	dK_2	$d\varphi_1$	$d\varphi_2$	$d\omega_2$
1.	0.52057 h	0	-0.04917 h	+0.05172 h	0	0	-1.18457 h
2.	0.63707 h	0	+0.05172 h	-0.04917 h	0	0	-1.12631 h
3.	0.52057 h	0.04918 h	-0.05038 h	+0.05051 h	-0.02560 h	-0.03133 h	-1.18667 h
4.	0.63707 h	0.04918 h	+0.05051 h	-0.05038 h	-0.03133 h	-0.02560 h	-1.12841 h
5.	0.52057 h	-0.04918 h	-0.05038 h	+0.05051 h	+0.02560 h	+0.03133 h	-1.18667 h
6.	0.63707 h	-0.04918 h	+0.05051 h	-0.05038 h	+0.03133 h	+0.02560 h	-1.12841 h
7.	0.57882 h	0.04918 h	+0.00007 h	+0.00007 h	-0.02847 h	-0.02847 h	-1.15754 h
8.	0.57882 h	-0.04918 h	+0.00007 h	+0.00007 h	+0.02847 h	+0.02847 h	-1.15754 h
9.	0.57882 h	0	+0.00128 h	+0.00128 h	0	0	-1.15544 h

WEIGHT AND CORRELATION NUMBERS

	Q_{K_1}	Q_{K_2}	Q_{φ_1}	Q_{φ_2}	Q_{ω_2}
Q_{K_1}	$82827.984/h^2$	$82834.060/h^2$	0	0	$67.20649/h^2$
Q_{K_2}		$82905.653/h^2$	0	0	$67.21846/h^2$
Q_{φ_1}			$8384.77365/h^2$	$-8281.89300/h^2$	0
Q_{φ_2}				$8384.77365/h^2$	0
Q_{ω_2}					$0.13755/h^2$

Figure 16b - COEFFICIENTS, WEIGHT NUMBERS AND CORRELATION NUMBERS OF EXAMPLE LEAST SQUARE ADJUSTMENT

$$V_y \left\{ = x \cos\varphi - h \sin\varphi \left(1 + \frac{y^2}{h^2}\right) \right\} dk_1 - \left\{ (x-b) \cos\varphi + h \sin\varphi \left(1 + \frac{y^2}{h^2}\right) \right\}$$

$$dk_2 - \frac{xy}{h} d\varphi_1 + \frac{(x-b)y}{h} d\varphi_2 + \left\{ \frac{(x-b)}{h} \sin\varphi - \left(1 + \frac{y^2}{h^2}\right) \cos\varphi \right\} h d\omega_2 - P_y$$

where: P_y (vertical parallax) $= y_2 - y_1$ (62)

This equation assumes the axis of rotation as the primary axis and uses orientation elements of both photographs. Similar correction equations may be developed taking either the k or w rotation as primary and using other combinations of (five) orientation elements.

The correction equation for each orientation point is found by inserting the model coordinates of the point equation 62 above. It can be seen that a solution for the corrections to the five orientation elements can be obtained from the vertical parallax measurements at a minimum of five orientation points. a least-square adjustment, however, will require at least one redundant observation. A minimum of six and possibly as many as nine or fifteen orientation points should be used for this adjustment. From the correction equations, normal equations can be set up and solved. The solution gives the corrections to the elements of the relative orientation and the weight and correlation numbers of these elements.

The influence of the relative orientation on the elevations of the model can be found from the basic parallax equation derived in Section B.

$$\Delta H = \frac{H}{b} \cdot \frac{H}{f} \Delta P \qquad \text{[See (4)]}$$

which can be rewritten as:

$$dh = \frac{h}{b} \; dP \qquad (63)$$

where dh is an error in model elevation, and dP is an error in the horizontal parallax.

Errors in the horizontal parallaxes caused by errors in the corrections of the relative orientation elements can be expressed as:

$$dP = -\frac{y}{h}(h \cos\varphi + x \sin\varphi)d\kappa_1 - (1 + \frac{x^2}{h^2}) h d\varphi_1 + \frac{y}{h}\left\{h \cos\varphi - (x-b) \sin\varphi\right\}$$

$$d\kappa_2 + \left\{1 + \frac{(x-b)^2}{h^2}\right\} h d\varphi_2 - \frac{y}{h}\left\{(x-b) \cos\varphi + h \sin\varphi\right\} d\omega_2 \qquad (64)$$

where: $dP = x_1 - x_2$

The weight number of the elevation at any point in the model can be found by equations 63 and 64, together with the weight and correlation numbers of the elements of relative orientation which

were found in the adjustment. The mean-square error in each model elevation can then be found as the product of the mean-square error of the vertical parallax measurements and the square root of the weight number of the elevation at that point.

A solution of this type was performed for a photographic system having a five-degree field of view. The ideal tilt of each photograph $\frac{\theta}{2} = 26^{\circ}\ 34''$ was approximately at 30° for ease in computation and the nine points indicated in Figure 16a were used as orientation points. The coefficients of correction equation 62 for these nine points are shown in Figure 16a together with the weight and correction numbers of adjustment.

Weight numbers of the model elevations of the same nine points were computed through equations 63 and 64 using the weight and correlation numbers of the orientation elements shown in Figure 16b. The accuracy of the vertical parallax measurements were assumed to be approximately equal to the measurement of horizontal parallax $M_{P_y} = M_{P_x} = \sqrt{2}\, M_x = 0.003$ millimeters. The product of this measuring accuracy and the square-roots of the elevation weight numbers then gave the mean-square errors in model elevation shown in Figure 16c for each of these points. For a flight height of 10,000 feet and a focal length of four feet, the resultant errors in terrain elevations will be:

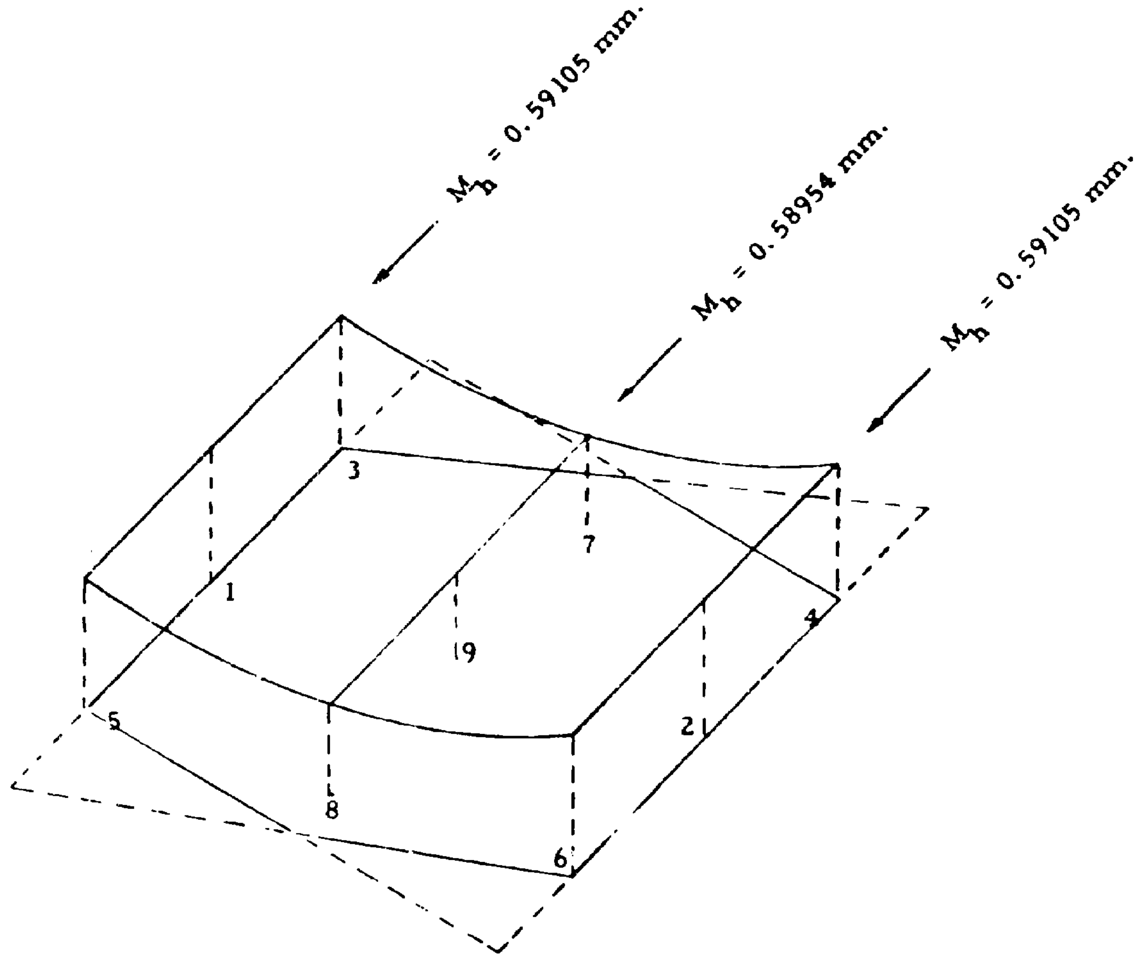

Figure 16c – MODEL DEFORMATION OF EXAMPLE RELATIVE ORIENTATION

$$M_h = 65.61 \text{ inches along each side and}$$

$$M_h = 65.44 \text{ inches in the center} \tag{65}$$

The nature of the deformation shown in Figure 16c is of major importance. This cylindrical bowing of the model is characteristic of a relatively weak determination of the corrections and is commonly referred to as the -cylinder or deformation. Thus it can be seen in this model that the primary source of elevation errors, if not the only sources, is the error in the correction of the elements. Because of this systematic dependence of all elevation errors on this one source, the error in the elevation difference between two points, say points one and nine, will not be found as

$$M_{\Delta H} = \sqrt{M_{h_1}^{\;2} + M_{h_9}^{\;2}} = 92.67 \text{ inches} \tag{66}$$

but as $d_{\Delta H} = M_{h_1} - M_{h_9} = 0.17$ inches

The remainder of the elevation error, 60 plus inches, is in actuality only a scale error in the model which has been shown to be of no consequence.

A comparison of equations 56 and 66 illuatrates that the errors in the measurement of elevation differences introduced by

a reasonably well-performed relative orientation will be insignificant.

(2) Atmospheric Refraction

The density of the earth's atmosphere and consequently its refractive index, will decrease with altitude above the surface. This decrease, however, is not linear. Thus, in order to accurately predict the path of an incident light ray through the atmosphere, an integration of the refrations of innumerable density layers would be required.

For the purpose of illustrating the insignificance of atmospheric refraction on the proposed photogrammetric measurements, we will simplify this problem by assuming that the photography is taken from above the atmosphere and that the total refractive effects will be present. This total refraction will effectively occur at altitudes in excess of about 8 kilometers (26,000 feet). At these altitudes, the distortion or apparent displacement of points on the terrain has been found to be approximately 2θ meters, where θ is any angle of incidence (in radians) up to 30 degrees.

It is obvious that corresponding points in each photograph of a stereo pair will have equal angular separations from the vertical in the direction normal to the flight path. Such points will receive equal refractive displacements in that direction. These displacements will have no effect on the relative orientation other than the fact that they are not eliminated and the

displacements parallel to the flight path will remain to effect the elevation measurements.

For a photographic system with a 53-degree angle of convergence of a five-degree field of view in each camera, the angles of incidence of the light rays will range from about 24 to 29 degrees for one photograph and from -24 to -29 degrees for the other. Through the relation above, the displacements of ground objects will then range from 33.07 to 39.85 inches and -33.07 to -39.85 inches, respectively. The center of the photographs will have an angle of incidence of approximately 26.5 degrees and -26.5 degrees, and object displacements of 36.42 and -36.42 inches.

These displacements in the direction of flight will introduce errors in the horizontal parallaxes and in the measured elevations. This relation will be:

$$dH = \frac{H}{b} \; dP' = \frac{H}{b} \; (d_1 - d_2) \tag{67}$$

where: d_1 and d_2 are the refractive displacements of an object in photographs 1 and 2. A solution of this equation for the displacements derived above would give a dH of 72.92 inches for the edges of the model (points 1, 2, 3, 4, 5, and 6 in Figure 16a) and a dh 72.84 inches for the center of the model (points 7, 8, and 9.)

The elevation errors caused by atmospheric refraction are similar to those of the relative orientation in that they are

systematically related to a common error source. Because of this relationship, the maximum error in the measurement of any elevation difference will not exceed approximately 0.08 inches. Here again, the major portion of the error (72 plus inches) is only a negligible scale error.

(3) Earth Curvature

The elevation error introduced by the curvature of the earth was shown in Section C to be approximately:

$$dH = \frac{M^2}{2R}$$

where M is the horizontal distance between two points in the terrain as computed in the orthogonal coordinate system of the instrument and R is the radius of the earth. When the model is properly leveled, the true vertical of a point is the center of the curved model, point 9, will correspond approximately to the vertical axis of the equipment. In this event, the maximum distance between this point and any other point in the model will be approximately one-half the longest dimension of the model. From Figure 16a this maximum distance can be found to be about:

$$M_{max} \approx \frac{h}{2} \tan\left(\frac{\phi}{2} + \frac{\theta}{2}\right) - \tan\left(\frac{\phi}{2} + \frac{\theta}{2}\right) = \frac{h}{2}(0.10908) \qquad (68)$$

Assuming the convergence angle and field of view stated previously and a maximum altitude of 25,000 feet, equation 68 will give as the maximum error in the elevation difference between two points a value of:

$$d\,\Delta H = 0.05 \text{ inches}$$

This value can be seen to be insignificant for measurements from 25,000 feet and ~~even~~ more insignificant for lower altitudes.

(4) Model Leveling

The model leveling error in the measurement of an elevation difference between two points will be dependent on the tilt of the model and the distance between the points in the direction of this tilt. The maximum distance between two points in the model can be found from Figure 16a, while the tilt error of the model will vary between the various leveling techniques used.

Assuming, as we have throughout this investigation, that no ground control will be available for either scaling or leveling of the model, the true vertical of the model must be obtained from data recorded in flight. The easiest method is to base the model vertical on the known vertical of the photography. In such a technique, the leveling will only be as accurate as the vertical stabilization of the photography. Present stabilized camera mounts are capable of maintaining a given photographic vertical

within approximately 10 to 20 minutes of arc. These capabilities would result in tilt errors of the model of only 0.3 to 0.6 per cent slope. These, then, would be the expected errors in determining the slope of the terrain which for aircraft operation can be considered negligible.

4. Summary

The preceding analysis of photogrammetric equipment and techniques indicates that direct-viewing stereo comparator procedures would be most applicable to the proposed application. Although such a procedure is slightly handicapped by the necessity for measuring all desired points before any of these may be reduced to terrain values, the quantity of measurements required can be reduced greatly when preceded by an intensive photographic interpretation. The photo interpreter can delete those areas in which extremely large elevation changes are evident, and reduce the extent of the photogrammetric measurements to only the relatively flat, questionable areas.

The precision of the stereo comparator equipment was shown to be approximately:

$$\frac{M\,\Delta H}{H} = \frac{1}{270{,}000} \qquad \left[\text{See (50)}\right]$$

This value was then reduced to approximately:

$$\frac{M \Delta H}{H} = \frac{1}{110,000} \qquad \text{[See (54)]}$$

by the limited depth perception of the operator. The relation $\frac{1}{2R}$ which was selected to indicate the measuring ability of the operator, however, is only an approximation and in many instances may be considered to be quite conservative. This relation will vary greatly between operators and between stereo models and is best derived through actual flight test procedures. Such tests will also indicate the image interpretability afforded by various terrain types.

The analysis of the effects of geometric errors on the measurements of rather abrupt elevation changes showed the limited importance of these effects. It may be reasoned that because of the minor influence of lens and film distortions on these specialized measurements, any camera system, including strip and panoramic cameras, might be used. Measurements over greater horizontal distances may be necessary and the possibility for minimizing these error effects with a framing camera would make this camera the best selection.

The error influences of the model deformation errors will have a negligible effect on the specialized measurements. Although these influences were also shown to have insignificant effects on measurements over greater horizontal distances (when considered individually), flight tests may indicate a significant summation of these influences in the more general

measurements.

In Section III, specialized equipment and techniques have been selected for a test procedure designed to substantiate the theoretical feasibility of the proposed operations. This test procedure will determine specifically;

a. The photographic scale and resolving power required for an accurate photo interpretive analysis of the various terrain features which will be detrimental to aircraft operations.

b. The overall accuracy of the photogrammetric procedures for measuring both abrupt and gradual elevation changes.

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II. TERRAIN SPECTRAL RECONNAISSANCE

A. INTRODUCTION

The information to be gathered by any passive type of airborne sensor is affected by three factors over which no control can be exercised: radiation incident upon the target, environment of the target, and nature of the target. However, the influence of these factors upon the type and quality of the resultant sensor data must be thoroughly understood in order to properly select and specify not only the sensors and their receptors, but the sensor data reduction and analysis equipment and techniques.

The problem to be considered here is one of investigating those equipments and techniques which might provide a means for identifying such characteristics of the earth's surface as roughness, compaction, composition, moisture content and vegetation types. By what means and methods may accurate and reliable ground property measurements be achieved?

This report is devoted to analyzing the requirements for an airborne information gathering system, determining the capabilities and limitations of various sensors and receptors, evaluating the effect of target characteristics upon the system, and considering methods of reducing and analyzing the resultant data.

The system concept is based upon the premise that virtually any object or condition at the earth's surface can be made to "sign" itself distinctively in some part of the electromagnetic spectrum. Additional

corollaries to this premise are: (a) spectral signatures using presently available films, filters, and other detectors can be established for targets of interest; (b) differences between signatures can be detected and amplified by certain data reduction techniques; and (c) the system should use multiple sensors to increase the level of confidence in identification of ground property measurements.

A reconnaissance system that covers a broad band of frequencies has the potential capability of carrying more information than a narrow band, if the broad band has equally fine resolution. It appears that a reconnaissance system capable of sensing over a wide range of wave lengths while at the same time obtaining adequate contrasts among the various spectral bands would satisfy the requirements for ground property measurements. Photographs of normal subjects can be altered and enhanced by judicious use of color filters, i.e., using one part of the spectrum to the exclusion of another part. Extending this principle to encompass a large part of the spectrum, including the infrared region, allows much freedom for a variety of contrast and differentiation of subjects which ordinarily tend to appear alike.

In order to record signatures of targets in any portion of the spectrum from 0.4 to 13 microns it is necessary to provide sensors using film as a receptor and sensors using infrared detectors as receptors. The spectral sensitivity of panchromatic film extends from 0.4 to approximately 0.7 microns. Infrared film is sensitive to approximately 0.9 microns. By dividing the spectrum from 0.4 to 0.9 microns into N number of bands by the use of selected filters, and taking simultaneous exposures of the same target through N number of lenses, the spectral

signature of the target in each of the discrete bands can be determined. The requirement for taking all exposures simultaneously using very closely matched lenses is dictated by data reduction techniques of density measurements and color separation which are discussed later.

A variety of infrared detectors may be utilized to record radiation in the 0.4 to 13.0 micron range. Figure 17 shows that only certain portions of the spectrum are capable of being transmitted with any appreciable energy level through the atmosphere. Therefore the choice of infrared detectors must be governed by matching their spectral sensitivity to the transmission windows that exist in the atmosphere. A more detailed discussion of detectors and the type of instruments in which they are employed follows in a later section.

The real strength of the proposed system is that it presents a group of simultaneous signatures of a target area for comparison, each of which constitutes a particular spectral response.

The problem of developing a practical spectral reconnaissance system requires balancing the limitations and requirements imposed by the following elements which will be discussed in subsequent sections.

(1) Available radiation, reflected and emitted.

(2) Radiation detectors

(3) Filters for selective energy separation

(4) Camera and IR devices

(5) Data analysis, including the determination of signatures of various types of targets.

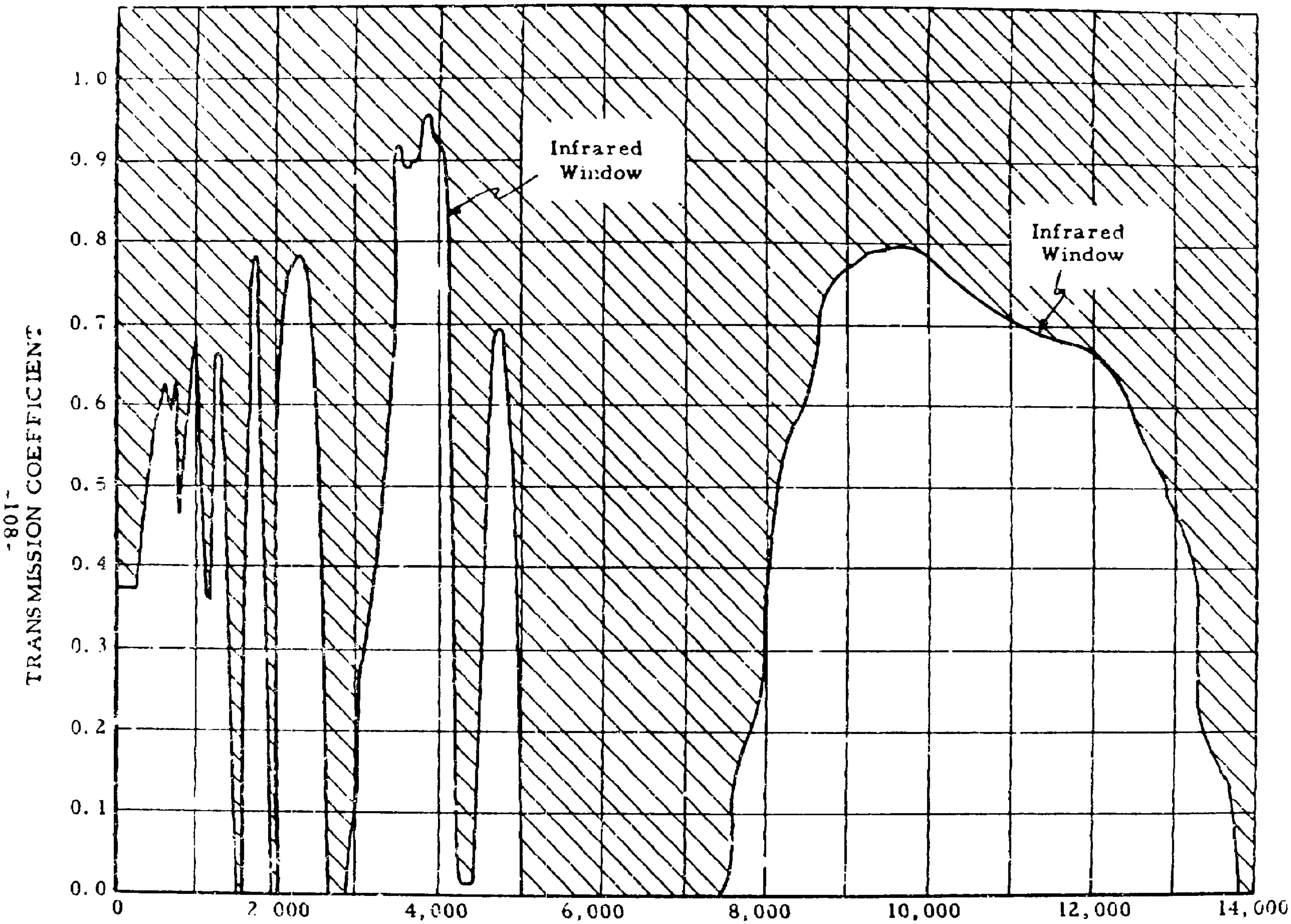

Figure 17 - TRANSMISSION SPECTRA OF THE ATMOSPHERE

B. FACTORS AFFECTING DETECTION AND RECOGNITION

1. Source

The only source of radiation to be considered here for practical use is the sun. Its radiation includes energy from 0.2 microns to approximately 3.2 microns. The solar radiation received outside the earth's atmosphere and also that proportion of the radiation which reaches the earth's surface, are shown in Figure 18. In addition to available sunlight, a second component, skylight, is also present. The ratio of these two components is dependent upon the sun angle and weather conditions. Color temperature values, as a function of weather and sun angle, are shown in Figure 19.

The wavelength scale has been distorted in Figure 20 in order to provide the same solar spectrum information in a uniform incremental energy plot. With a linear, rather than a logarithmic ordinate, this type of plot simplifies the visualization of the spectral effects when film-filter responses or an infrared detector response is compared.

The spectral response curves of several photographic emulsions and two infrared detectors are shown in Figure 21 with the same incremental solar energy wavelength scale as Figure 20.

The radiation incident upon the earth's surface is modified and altered before it is received at the detector by; (a) reflection from the target, (b) absorption and re-radiation as thermal energy, (c) target characteristics (d) atmospheric attenuation, and (e) sensor system components such as the optics, shutter, and filter. The effect of the

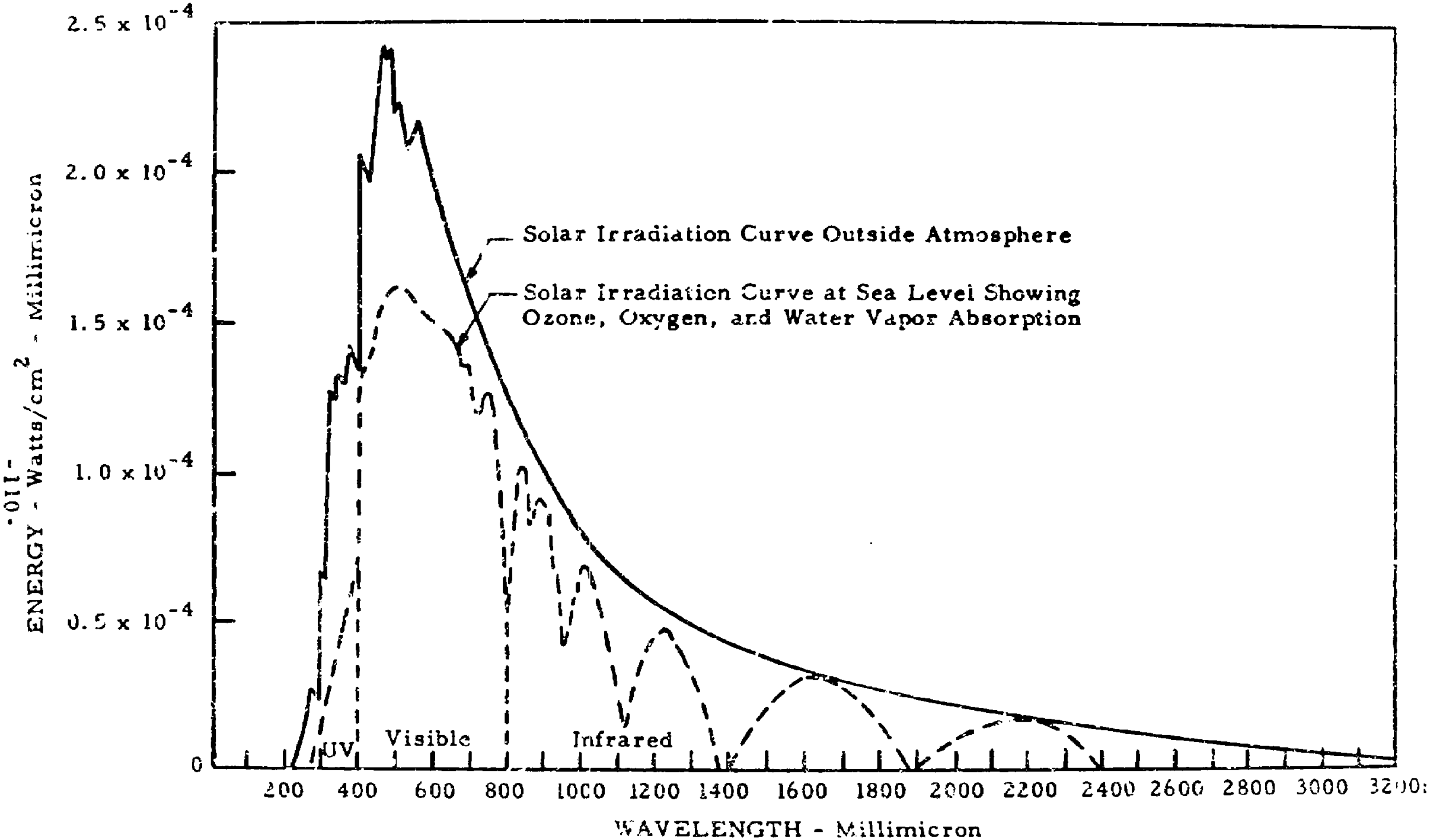

Figure 18 - SPECTRAL DISTRIBUTION OF SOLAR ENERGY WITH SUN DIRECTLY OVERHEAD

CONDITION	April and May	June and July	Sept. and Oct.	Nov., Dec. and Feb.
Direct sunlight alone, 9 a.m. to 3 p.m.	5800°K	5800°K	5450°K	5500°K
Direct sunlight before 9 and after 3	5400	5600	4900	5000
Sunlight plus light from clear sky . . .				
9 a.m. to 3 p.m.	6500	6500	6100	6200
Before 9 and after 3	6100	6200	5900	5700
Sunlight plus light from a hazy or slightly overcast sky	5900	5800	5900	5700
Sunlight plus light from 25% to 75% overcast sky	6450	6700	6250	....
Totally overcast skylight	6700	6950	6750	....
Light from hazy or smoky sky	7500	8150	8400	7700
Light from clear blue sky...				
9 a.m. to 3 p.m.	26,000	14,000	12,000	12,000
Before 9, after 3	27,000	....	....	12,000

Figure 19 - AVERAGE COLOR-TEMPERATURES OF DAYLIGHT FOR VARIOUS SEASONS AND WEATHER CONDITIONS
(Light Received on a Horizontal Plane)

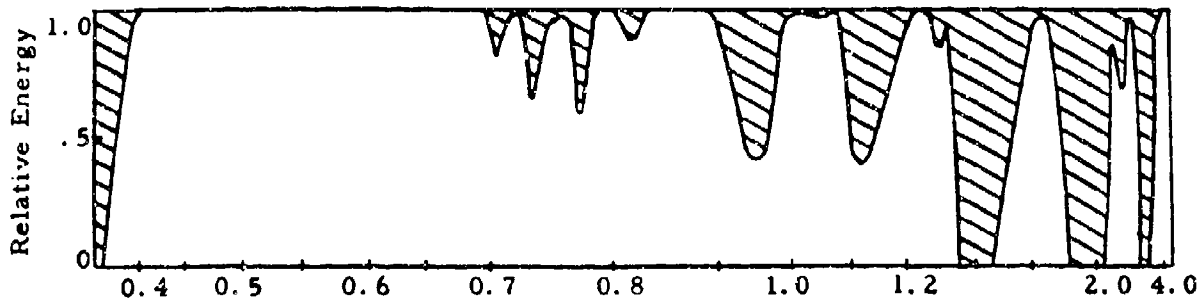

Figure 20 - SOLAR ENERGY REPLOTTED TO SHOW RELATIVE ENERGY IN INCREMENTAL WAVE LENGTH INTERVALS

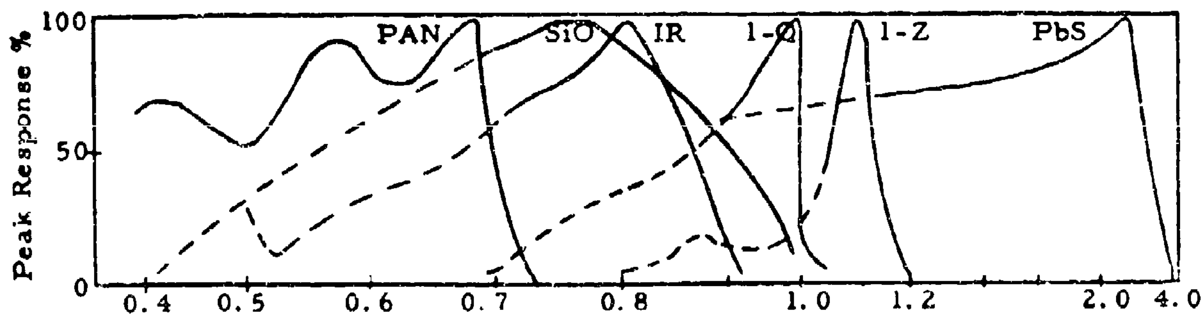

Figure 21 - FILM AND PbS SENSITIVITY versus WAVE LENGTH

sensor system components will be discussed in a following section.

a. Reflected Radiation

The reflection of a target is the ratio of the radiation reflected by the target to the radiation incident upon it. The total energy reflected from a target is the product of its reflectivity and its irradiance or the radiation density incident upon it. Since the radiation incident upon the earth does not extend beyond approximately 3.0 microns, no reflected energy beyond this limit can be expected at the detector. Sensors using film, silicon and lead sulfide detectors would be employed to record reflected radiation.

Very few surfaces have a flat reflection response for all wavelengths. Terrain and natural object targets particularly do not reflect equally well at all wavelengths. It is this characteristic that offers a method of detecting and recognizing one object or type of terrain from another.

b. Emitted Radiation

The total radiation of any target is the sum of its reflected radiation and its emitted radiation. According to general physical theory, all objects emit radiation. The total emitted radiation depends upon the temperature, the emissivity, and the area of the object. The spectral content of the radiation is a function of the temperature. For usual ambient temperatures the maximum of the radiation density curve occurs at approximately 10.0 microns. The primary objective of the

reconnaissance system is to detect, locate, and identify targets of different soils and vegetation. The target detecting ability of infrared sensors is generally measured in terms of noise equivalent temperature difference which is defined as the temperature difference necessary to produce a S/N ratio of 1. However, a target whose emissivity differs from another target can also be detected even though the temperature difference is 0. This can be measured in terms of noise equivalent emissivity difference which is defined as the emissivity difference to produce a S/N ratio of 1. See Appendix A for an example using an interferometer-type spectrometer with a thermistor detector.

2. Atmospheric Transmission

Since the reconnaissance system will be operated over fairly long path lengths, atmospheric absorption of radiation will be an important factor. In contrast to the visible region where the transmission is uniformly high, transmission in the infrared region is confined to well-defined windows separated by deep absorption bands associated with carbon dioxide and water vapor. Atmospheric transmission as a function of wavelength is shown in Figure 17.

3. Target

The target in this case is the surface of the earth. The information to be gathered from the target is its thermal emissive characteristics and differences. The termal emission of the earth is influenced by a

great number of factors.

The earth/air interface is either a land, snow, or water surface. At many locations, the physical structure of the interface will be exceedingly complex. The land surface can be covered with seasonally varying vegetation of diverse types. Considerable variation is produced by small scale terrain features, differences in soil moisture, cultivation, etc. A snow surface is affected by aging. All of these conditions reflect themselves in the thermal emissive aspects of the earth.

The factors which determine the temperature of the earth/air interface may be separated into four classes, according to surface characteristics which influence:

(a) The net radiation intensity, such as albedo and color,

(b) The convective heat transfer into the air, such as surface roughtness,

(c) The conduction of heat into the ground, such as thermal admittance, and;

(d) The transformation of radiation energy into latent heat, such as dampness at the surface or available soil moisture at the ground level.

Near noontime in clear summer weather, a considerable portion (60-70%) of the solar constant penetrates to the lower boundary of the atmosphere. There a modification of air temperature starts essentially at the ground level. This process is controlled by the earth/air interface.

Any variability of the surface features causes a considerable variability of the thermal response to the forcing function of net radiation. When a surface is covered with dense vegetation, the plants themselves act as radiating surfaces with the general result temperature maxima are more likely to be found near the top of vegetation than at the earth/air interface.

A special and rather extreme case of surface roughness is represented by forests. The trees intercept solar radiation and the heat absorbed is given off into the air which is trapped between the stems. Although deep snow may lie on the ground, daytime temperature in wooded areas in spring can reach 60°F.

If soil moisture is readily available at the earth's surface, the emitted part of net radiation is significantly reduced due to the latent heat of evaporation.

The effect of color on net radiation can be shown by the results of an experiment made in India by Ramdas and Dravic. They dusted a test surface with a very thin layer of white powered lime. The treated section was up to 27°F cooler than the control surface.

The following factors are important in influencing the pattern of soil temperature variations at any given locality, and must be investigated and assessed before a set of observations can have full value. The factors are: (1) type of soil; (2) state of compaction of soil; (3) moisture content of the soil; (4) type of surface cover, including its color; (5) amount and nature of traffic over site; and (6) local climatic conditions.

An infrared system for detecting tanks and vehicles must do so against background radiation from trees, bushes, buildings, and the

ground. The problem is to detect differences between the targets comprising the normal background radiation. Special techniques must usually be employed for discriminating the source or target against its natural background.

All of these objects radiate IR energy. The spectral characteristics of the radiation emitted depend upon both the source temperature and such surface characteristics as emissivity and reflectivity. Surfaces may both emit IR energy and reflect IR energy from the sun.

A target at a different absolute temperature or emissivity from its surroundings can be detected. The absence of sharp thermal discontinuity between objects and surroundings greatly complicates the problem of detection of terrestial targets.

Since we are concerned with detecting thermal differences within the 4 to 13 micron band, a method of preventing radiation in other bands from reaching the detector must be used. During the day the earth is heated to approximately $300^{\circ}K$ by the sun's radiation, and radiates as a grey body. In addition to radiating with a peak spectral intensity at 9.7 microns, it also reflects the sun's radiation at shorter wavelengths out to approximately 3 microns. A filter must therefore be employed with an IR thermal detector operating in the daytime. Additional band pass filters may be used to allow only those portions of the target energy to be recorded that contain the signature information.

4. Season and Geographic Location

The general surface temperature changes with season and geographical location, and this change can produce significant differences in

radiance contrasts as well as in total emitted radiation. The temperature range from summer to winter in a temperate climate is approximately 40°C (from -10°C in midwinter to +30°C in midsummer). The difference in total radiant emittance, $W_1 - W_2$, between two targets of emissivities E_1 and E_2 and temperatures T_1 and T_2 is given by:

$$W_1 - W_2 = E_1 \sigma T_1^4 - E_2 \sigma T_2^4 \tag{69}$$

The difference in radiant emittance between two targets separated by a constant temperature difference will be greater at higher temperatures. For example, consider two black-body emitters which are separated by a temperature differential of 2°C in summer and in the winter.

The incidence of all conditions mentioned above is strongly dependent on geographical location. In addition, the geographical location is related to the general terrain background of the presentation. These general backgrounds may be rock, sand, snow, tundra, or jungle, to name a few, and all present quite different problems in interpretation.

The effect of reduced radiance contrast in winter (for the same temperature difference in the object field) is further aggravated by the temperature differences themselves which are, for terrain features, generally smaller in winter than in summer. This is because radiation exchange values are higher in summer. Since the temperature of other objects on the ground is generally determined by the competing effects of earth radiation and conduction from below and sky radiation from

above, considerably greater temperature differences between, say asphalt and grass, are to be expected in summertime. Stated differently, we may imagine temperature structure in terrain to be generated by a "driving force" whose magnitude is determined by the difference between soil temperature and "apparent" sky temperature; i.e., the radiation exchange value. This driving force is considerably greater in summer.

C. IR DETECTION SYSTEMS

1. Detectors

The present state-of-the-art in IR detectors includes a wide variety of detector types. These include photoconductive, photoemissive, thalofide cells, and thermal detectors, such as thermocouples, thermopiles, and different types of bolometers. These detectors have varying properties and applications and may be classified in numerous ways. This report will use a broad classification consisting of the wavelength regions of the IR spectrum in which they are most applicable.

The IR spectrum may be broken into three main areas, the near IR, the intermediate IR, and the far IR. The near IR is generally considered from approximately 0.7 to 1.5 microns. The intermediate IR region extends from 1.5 to 5.6 microns. The far IR covers the region from approximately 5.6 to 1000 microns; however, for practical purposes the useful portion extends only to approximately 13 microns, due to atmospheric absorption.

The selection of a detector for a particular application will depend upon whether the prime objective is merely to detect the presence of a source or to obtain a radiometric measurement of its intensity and spectral distribution. Obviously if the latter is required, the wavelength response of the detector must cover the complete range of expected frequencies with a minimum variation in spectral sensitivity. Thermal detectors fulfill these requirements in cases where a wide spectral region is to be covered and intense sources are available. Greater sensitivity can be obtained in limited regions with the more sensitive photoconductive or photovoltaic detectors.

a. Near IR Detectors

This group consists primarily of the three basic types of photoelectric cells (photoemissive, photoconductive, and photovoltaic) and some phosphors. In photoemissive cells, IR radiation incident on the sensitive surface of the cell causes the photoemission of electrons. In the photomultiplier tube, the electron stream from the cathode is amplified by employing the principle of secondary emission from multiple dynodes. This results in a detector with very high detectivity and rapid response in the near IR. Many of the photoemissive devices use silver-oxygen-cesium as the sensitive surface. A silicon solar cell is an example of a photovoltaic type having a spectral range of 0.4 to 1.2 microns.

Photoconductive cells make use of the change in the originally high resistance of semiconductor materials cuased by incident IR radiation.

Many lead sulfide detectors of this type are commercially available. Thallium sulfide cells, using thallium oxysulfide as the sensitive surface, are commercially available with a spectral response out to about 1.5 microns. Germanium photodiodes are also used in the near IR. The photodielective effect, which makes use of the change in dialectric constant of a material, due to incident IR radiation, is utilized in detectors employing zinc sulfide, lead sulfide, cadmium sulfide, cadmium selenide, lead selenide, cadmium telluride, zinc telluride, and combinations of these.

Photoquench phosphors have found application in image converter tubes, making use of the decrease in the fluorescence of a screen, of zinc sulfide or other material activated by ultra-violet light or alpha particles, when an IR image is projected on it. The metoscope is an example of the use of such phosphors.

b. Intermediate IR Detectors

The majority of the intermediate IR detectors are of the photoconductive type and employ semiconductor materials. These detectors made of semiconductor crystals, change their electrical conductivity when exposed to IR radiation and are generally of either the intrinsic or impurity type. In an intrinsic photoconductive material, the energy absorbed by electrons from incident IR radiation excite forbidden bands, within which no energy levels can be occupied by electrons, to energy levels in the conductive band. Impurity photoconductive materials, also

called doped materials, are made by introducing small amounts of a chemical impurity during the crystal growing process. These materials contain energy levels in the forbidden band. Indium antimonide is an example of the intrinsic type. Examples of the impurity type are indium or gold in silicon or in germanium.

The various types of photoconductive detectors have different properties and applications. Lead sulfide detectors have the highest detectivity but are limited in spectral range. Their range may be extended by cooling at liquid nitrogen temperatures, but only to about 4 microns. However, this type of cell has reached the highest state of development. Lead telluride detectors are available with a cutoff of approximately 5.5 microns in either a single cell or as multiple cells forming a mosaic. Lead selenide detectors are superior to lead telluride in terms of absolute spectral response, but require cooling for optimum detectivity. Recent advances in indium antimonide detectors have resulted in flat spectral responses out to 6 microns. Still primarily in the development stage are detectors of germanium, silicon, and alloys of these materials. Some gold and antimony doped germanium detectors are in limited production.

c. Far IR Detectors

Far IR detectors may be considered thermal detectors and measure incident IR radiation by a change in various physical properties caused by an increase in temperature of the sensitive surface. Thermal detectors have flat response curves, but relatively low detectivity.

Widely used thermal detectors are thermocouples, thermopiles, and bolometers.

A thermocouple makes use of a pair of thermo-electric junctions of dissimilar metals with one junction blackened to receive IR radiation. The change in temperature due to incident IR radiation produces an output voltage. The other junction is shielded to form part of a balanced bridge circuit to counteract environmental changes. A number of thermocuples connected in series produce a thermopile. Widely used thermocouples are the silver-palladium thermocouple, the Weyrich vacuum thermocouple, and the Harris and Scholp thermocouple.

Bolometers consist of blackened strips of metal backed with glass or film. Incident IR radiation increases the temperature of the strip with the resulting change in resistance causing a potential drop across the bolometer which is measured by a balanced bridge circuit. Bolometer types available include Polaroid bolometers, Strong bolometers, columbium nitride bolometers, evaporated gold bolometers, and thermistor bolometers.

2. Equipments

a. Spectrometers

The majority of the standard type spectrometers are not particularly suited to operation from an aircraft due to the long scan times and small slit apertures required. A number of available instruments have been examined and the most versatile appears to be an interfero-

meter spectrometer recently developed by Block Associates. The advantages of this instrument are its greater sensitivity by several orders of magnitude; small size and light weight; rapid scan; broad spectral capibility (0.4 to 13 micron measurements are possible with a choice of several detectors to cover this range), all of which make it a particularly useful tool for this application. When spectrograms are wanted for reflected energy as well as radiant energy, a wide wave length acceptance band is required. Figure 22 illustrates that to include the peak energy output between 6000°K and 200°K the broad spectral capability of the Block unit is required. Four spectrometers, each with a selected detector for a particular part of the spectrum will provide coverage for this entire range. Figures 23 and 23A show a detector head and control unit, and a block diagram on the principle of operation. The impinging radiation is divided by the beam splitter upon entering the detector head. The radiation is reflected by two mirrors and is superimposed at the detector. The movement of one of the mirrors by the saw tooth oscillator causes the superimposed energy to be in phase at various wave lengths as the mirror traverses its scan. By knowing the relationships that exist in the detector head the wave lengths which are in phase can be determined for any given time. The signal recorded on tape is an integration of all wave lengths. Varying wave lengths are recorded as varying audio frequencies and by playback of the tape through a wave analyzer a chart of amplitude vs. frequency is obtained. By calibration this is converted to relative intensity vs. wave length. The spectrometer data acquisition system being used in the VELA program is shown in Figure 24. The system

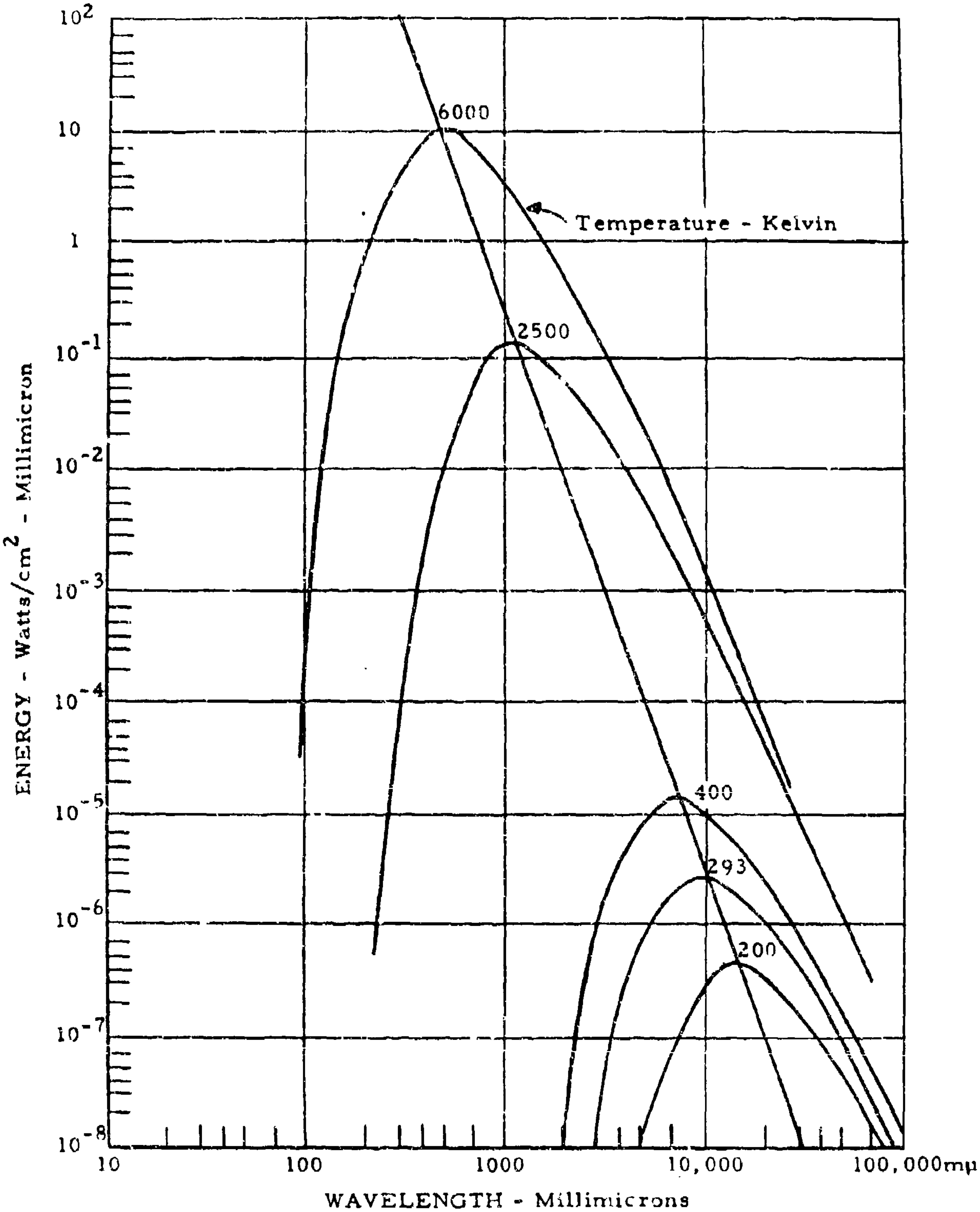

Figure 22 - BLACK BODY RADIATION CURVES

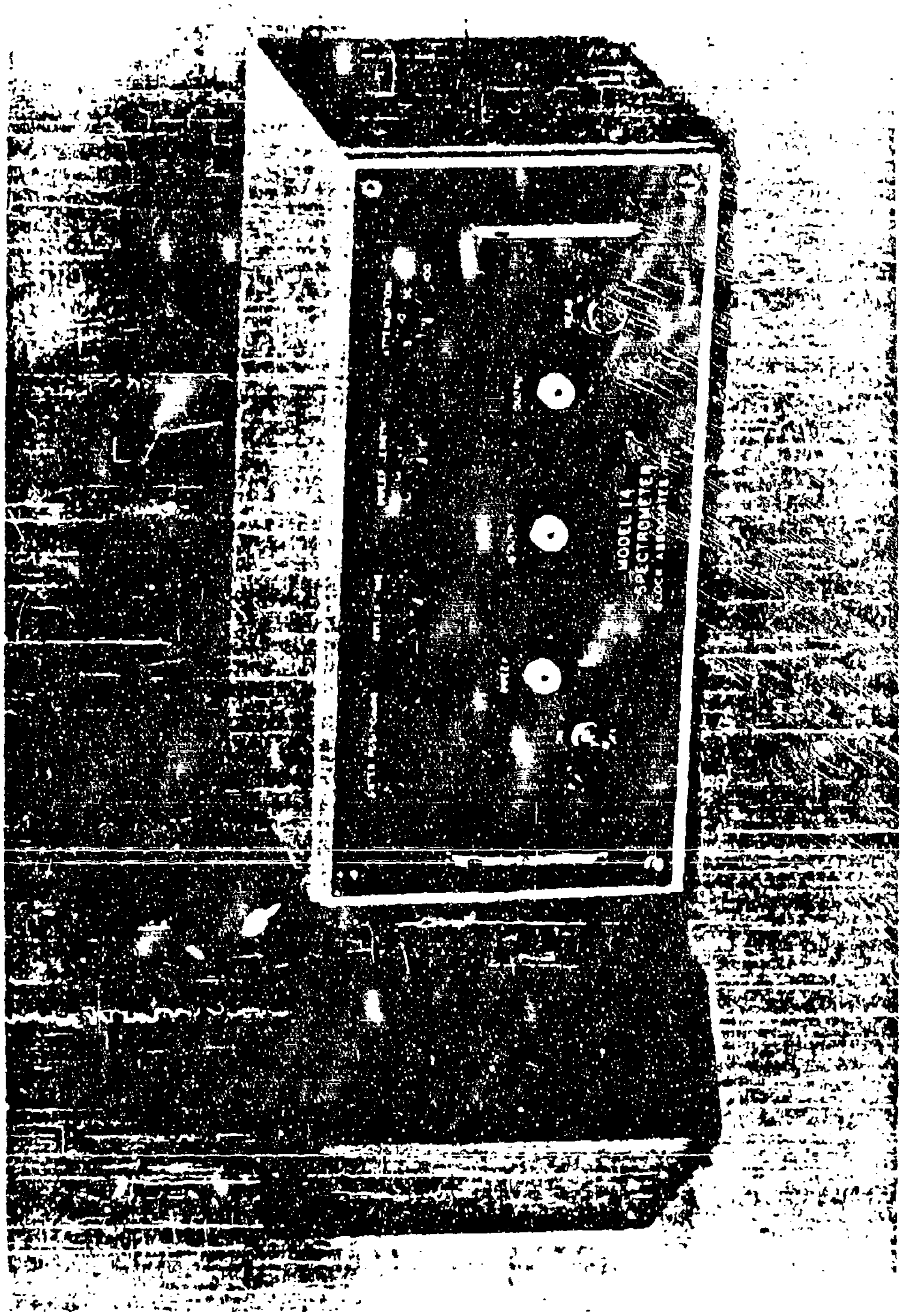

Figure 23 - SPECTROMETER DETECTOR AND CONTR L UNITS

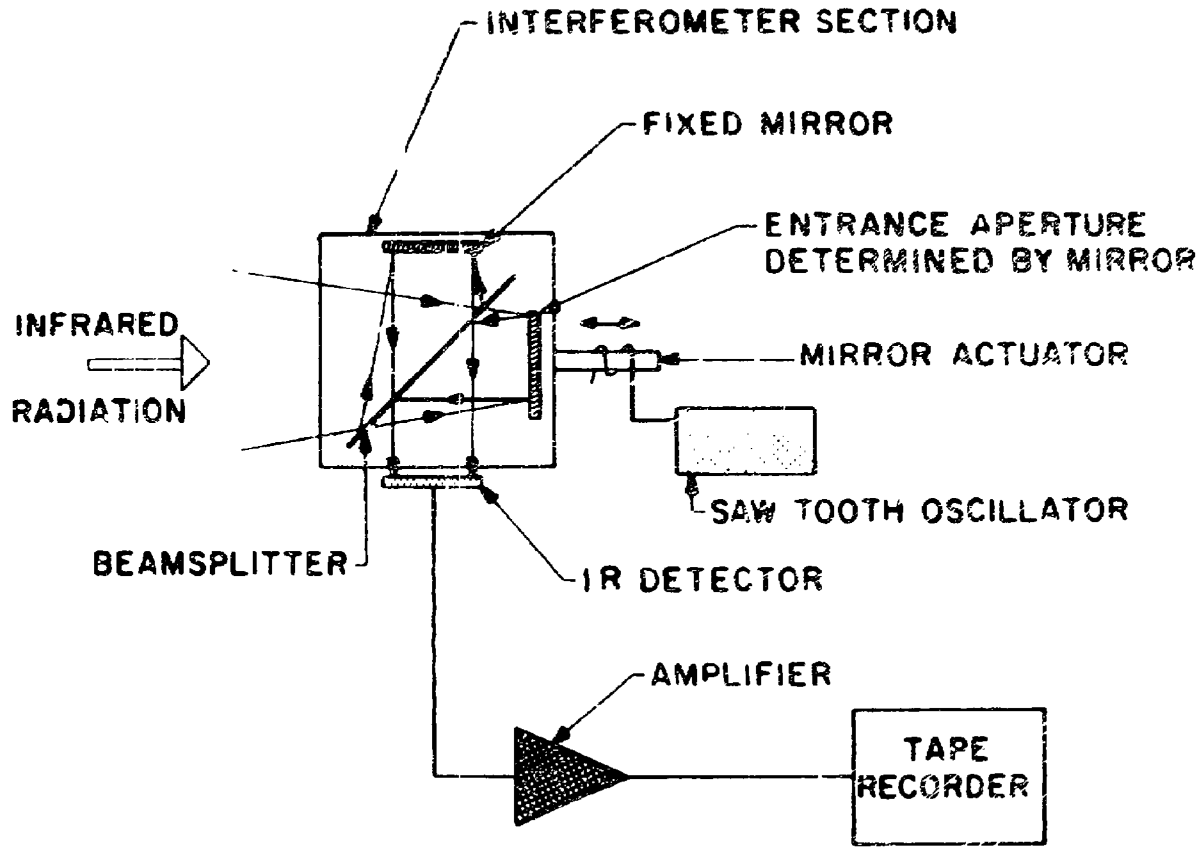

Figure 23a - INTERFEROMETER SPECTROMETER

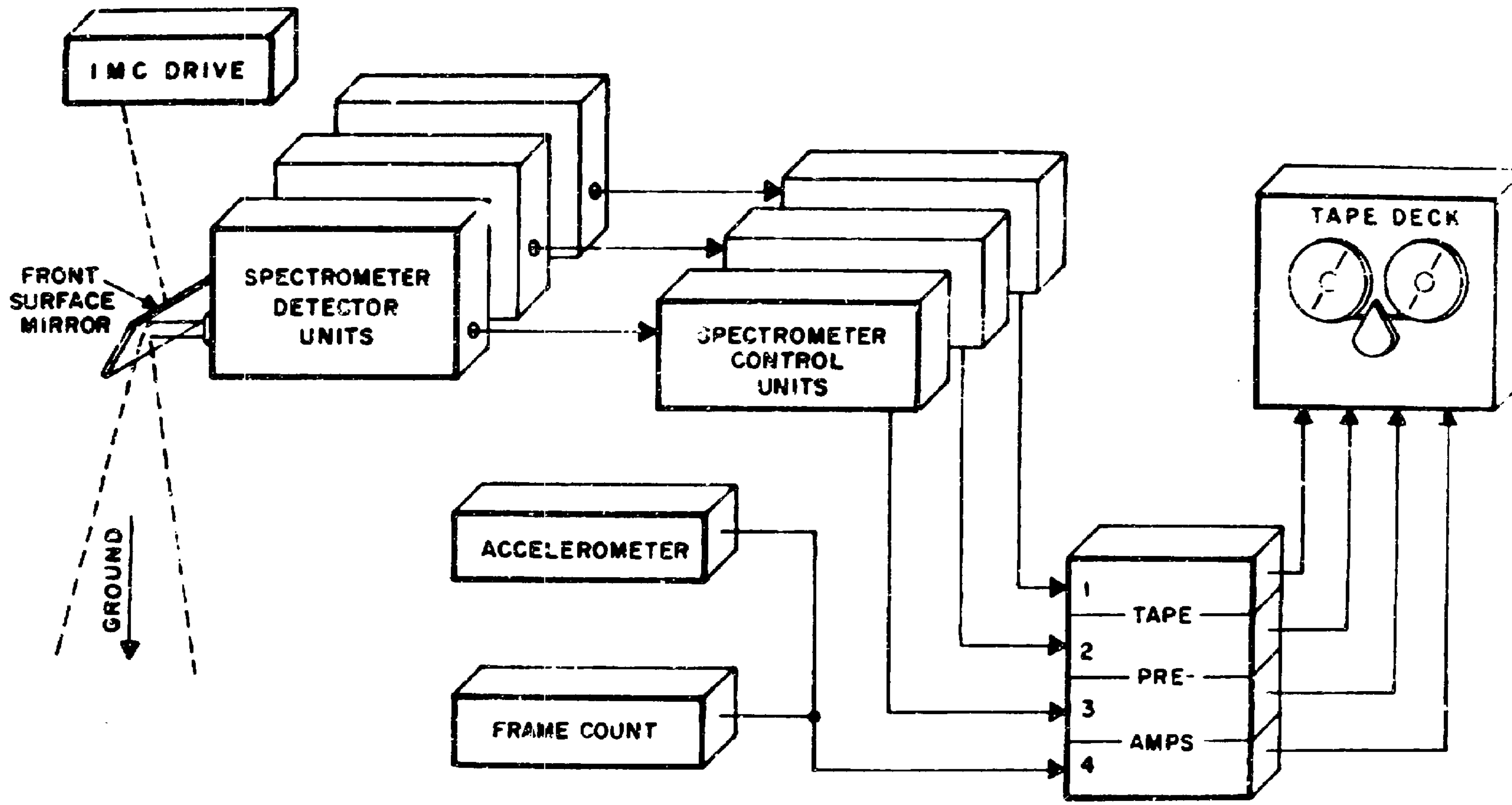

Figure 24 - SPECTROMETER DATA ACQUISITION

with an additional spectrometer would cover the broad spectral range required.

b. Thermal Mappers

The usefulness of an infrared strip map as a source of intelligence is a function of resolution (ground resolved distance), tonal contrast between the targets and their environment, and the distortions in the presentation. These parameters are influenced, to a large degree, by instrumental and operational variables such as the instaneous field-of-view, spectral region of operation, scan pattern, flight parameters, and display techniques. A general schematic diagram of a scanning system is shown in Figure 25. More advanced higher resolution systems use a line scan tube as the display device to the film. Later classified versions of the Reconofax system are recommended for maximum detail and sensitivity. The tonal gray scale which appears on the final map is a function of the relative energy impinging upon the detector at any instant in time. This tonal pattern is greatly changed by the spectral sensitivity of the scanner system. Selective filtering will enhance certain targets by changing the tonal contrast of the image.

D. SPECTRAL CAMERA

1. Requirements

The basic requirement of the spectral camera is to enhance the

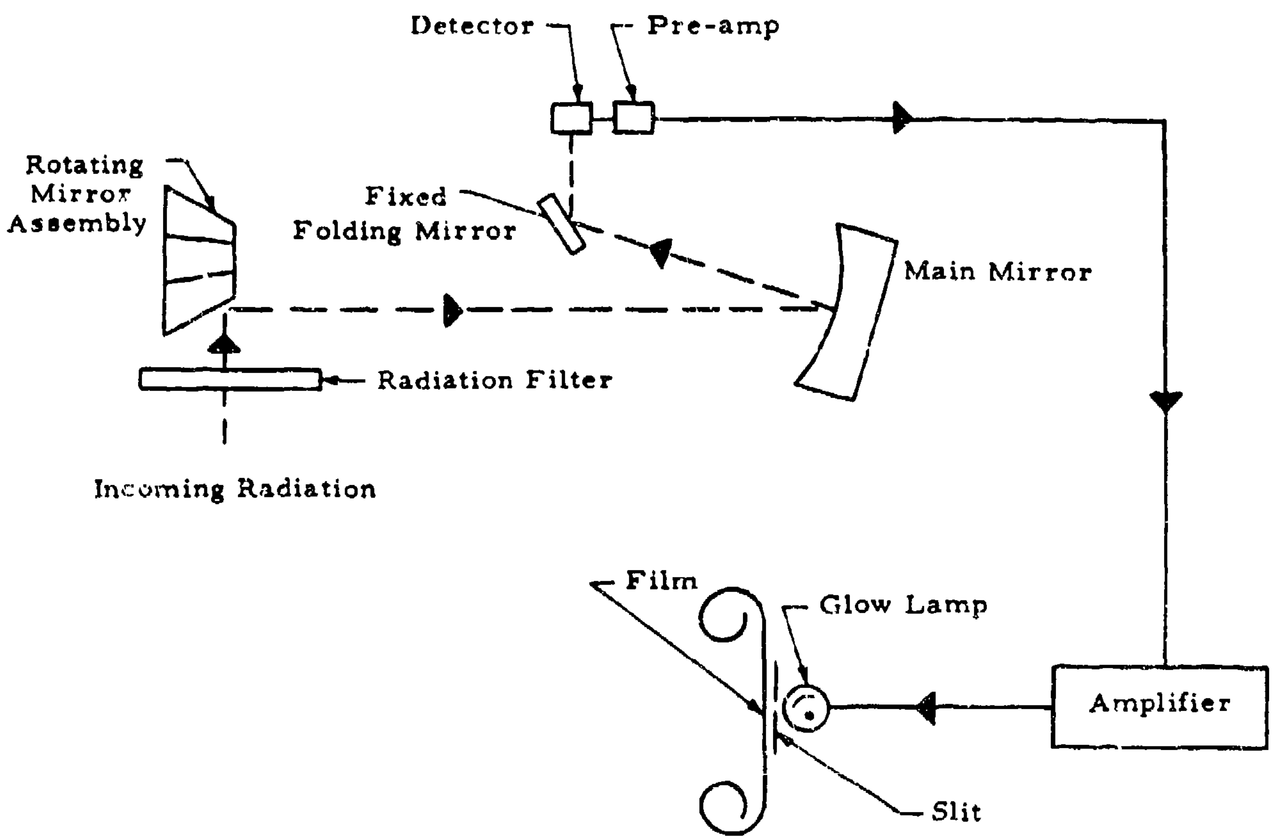

Figure 25 - SCHEMATIC DIAGRAM OF SCANNING SYSTEM

tonal difference between objects and to provide "signatures" of the objects in question. To perform this task the spectral camera will require a multi-lens system and the appropriate resolution and focal length to resolve the objects in question.

The objects must be larger than the "just resolvable" dimension so they will not be lost during color enhancement and density measurements. Also since high speed aerial films, especially infrared film, have poor resolution, a long focal length and relatively low altitudes must be used.

The payload characteristics are dependent upon the sophistication of the data-reduction equipment, that is, spectral signatures are derived from density measurements taken from the films. The size of the area from which the density can be determined and the accuracy of location of the densitometer aperture, combined with the scale factor, determine the minimum object size for which a signature can be obtained. The registration obtained in image superimpositio determines the resolution limit of the color derivative output and this, combined with the scale factor, determines the minimum ground size which can undergo color enhancement.

Therefore, once specifications for a ground data-reduction system and the object detection size required are stated, the system scale factor (flight altitude and focal length) can be defined.

The two preceding statements can be simply stated as:

$$fl = \frac{(A_d + 2L_d)h}{O_s} \; ; \qquad \text{and} \qquad fl = \frac{h}{R_c \, O_s} \; ;$$

when $A_d > \frac{1}{2 R_s}$ and when $R_c < R_s$

fl = Camera focal length required

A_d = Aperture of densitometer

L_d = Locating error of densitometer

h = Flight altitude

O_s = Object detection size required

R_c = Resolution of color derivative system

R_s = Resolution of camera system

Work presently being done in this field with straight-forward density measurements and pin registration devices would provide a system with the following specification.

3.3 feet - Object detection size for color enhancement

12.0 feet - Object detection size for density measurement

10,000 feet - Flight altitude

24 inches - Focal length lenses

Both object detection sizes could be reduced by a factor of four with more sophisticated data reduction equipment.

The number of lenses required for a spectral camera would be determined by the data-handling techniques used and the signatures of the objects in question. Figure 26 shows four spectrograms obtained with eight bands which will be used in a nine-lens spectral camera. The technique employed will be explained later in the document. It is

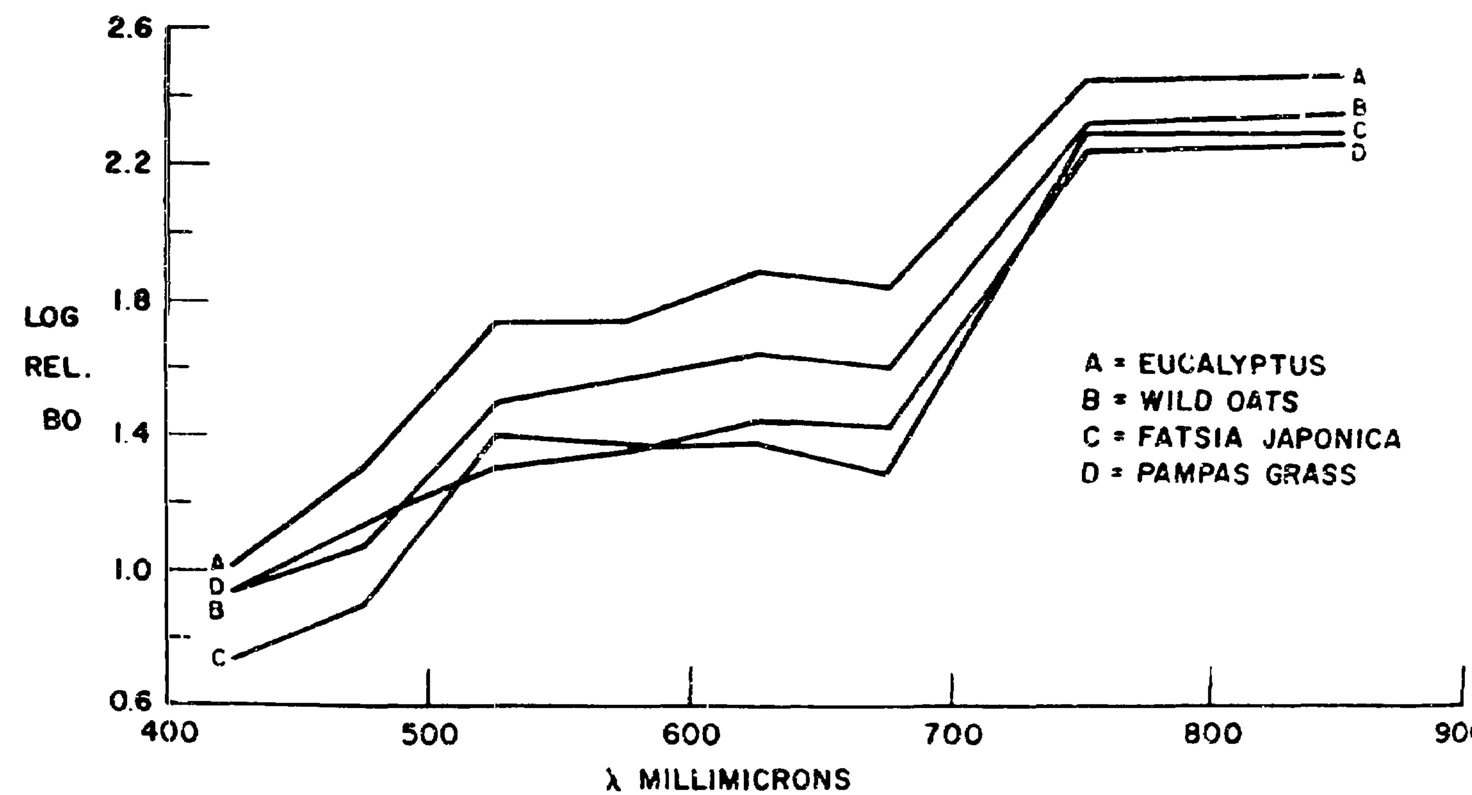

Figure 26 - SPECTRAL SIGNATURE CURVES

apparent from these curves that less than eight bands will indicate the key points of the spectrograms. The bands used (wavelength and bandwidth) will be dependent upon the subjects being investigated. It is felt that for a specific system intent, less than nine bands which would be selected for the key identification wavelengths would provide the signatures required. The color enhancement technique to be explained uses four of the eight bands.

An outline of the physical requirements is listed below.

(a) Number of lenses - 3 to 9

(b) All frames exposed simultaneously

(c) All lenses must have identical focal lengths

(d) All lenses must have same distortion characteristics

(e) Two or three types of film

(f) Identical IMC for all frames

(g) Slow shutter speed

(h) Incident light patch recorded on films through multiband filters

From the aforementioned outline it is evident that the spectral camera is not a normal aerial camera but will require certain special design features. One of the most critical problems in the multiband system is providing precise register of the individual separations when they are ultimately combined. The matching of the lenses and exposures at the same instant in time with identical IMC becomes the key items in

the manufacture of an aerial spectral camera system.

2. Films and Filters

These two items are quite interrelated as filter bandwidth required determines the film speed needed. Figure 27 shows eight spectral bands covering 400 to 900 millimicrons by the use of panchromatic and infrared film. The narrowness and peak transmission of the filters used with the panchromatic film necessitates an f 2.8 lens system and Plus X aerocon film. Broader band filters or filters with higher peak transmission in the acceptance bands would allow the use of slower, higher resolution films and/or larger f number lenses. Aerial infrared film has low resolution and, until a higher resolution infrared film is produced, a spectral camera will be resolution limited by infrared film. The filter factors that accompany the filters shown in Figure 27 are as large as 100, which is equivalent to taking a film with a speed of 160 and reducing it to 1.6. It is also evident from examination of Figure 27 that infrared film retains the inherent blue sensitivity of silver halides and can be used for spectral photography at the extreme short end of the spectral band.

Wratten filters are readily available and will provide (in combination) a selection over most of the spectral range in use. These are selective absorption filters made by adding organic dye to gelatin. Some of the filters have a short life when exposed to sunlight. To obtain narrow bands with these filters low transmission usually must be accepted within the bandwidth accepted.

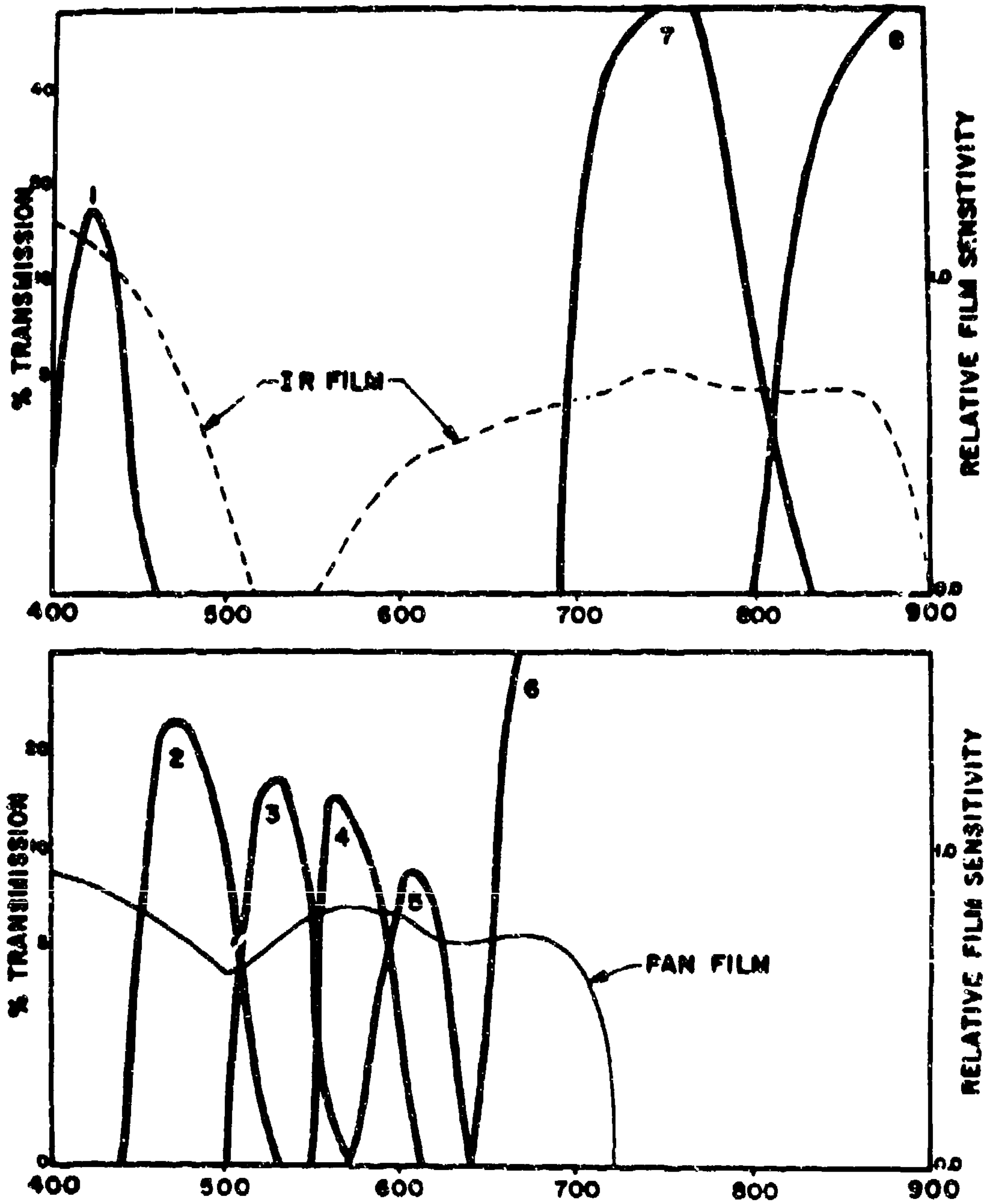

Figure 27 - FILTER TRANSMISSION AND FILM SENSITIVITY versus WAVELENGTH

Interference filters are not so conveniently available in such a variety as absorption filters, but they offer sharper cutoff and greater transmission within the acceptance band. These filters can be made to reflect the light they do not transmit (dichroic filters), therefore allowing a dividing of the spectrum and obtaining two or three bands from one lens.

Above all it must be pointed out that camera design, film, and filters constitute an integrated package and must be designed and selected for the particular goal in question.

3. Sample Systems

Two systems will be mentioned to illustrate the wide variety of approaches possible.

a. The first is a brief summary of a nine-lens camera now under construction. The camera consists of an A-9B aircraft camera magazine modified for IMC operation and employing three 70-mm film spools, and a lens cone containing nine matched six-inch focal length lenses. One focal plane shutter with nine slits simultaneously exposes all nine formats. A block diagram and photograph are shown in Figures 28 and 29. This camera will be used in a test program to verify the spectral techniques discussed and allow examination of nine bands for the wavelengths which will prove most useful. Another small camera will be provided to expose reference illumination patches on similar films through identical multiband filters during photography. The

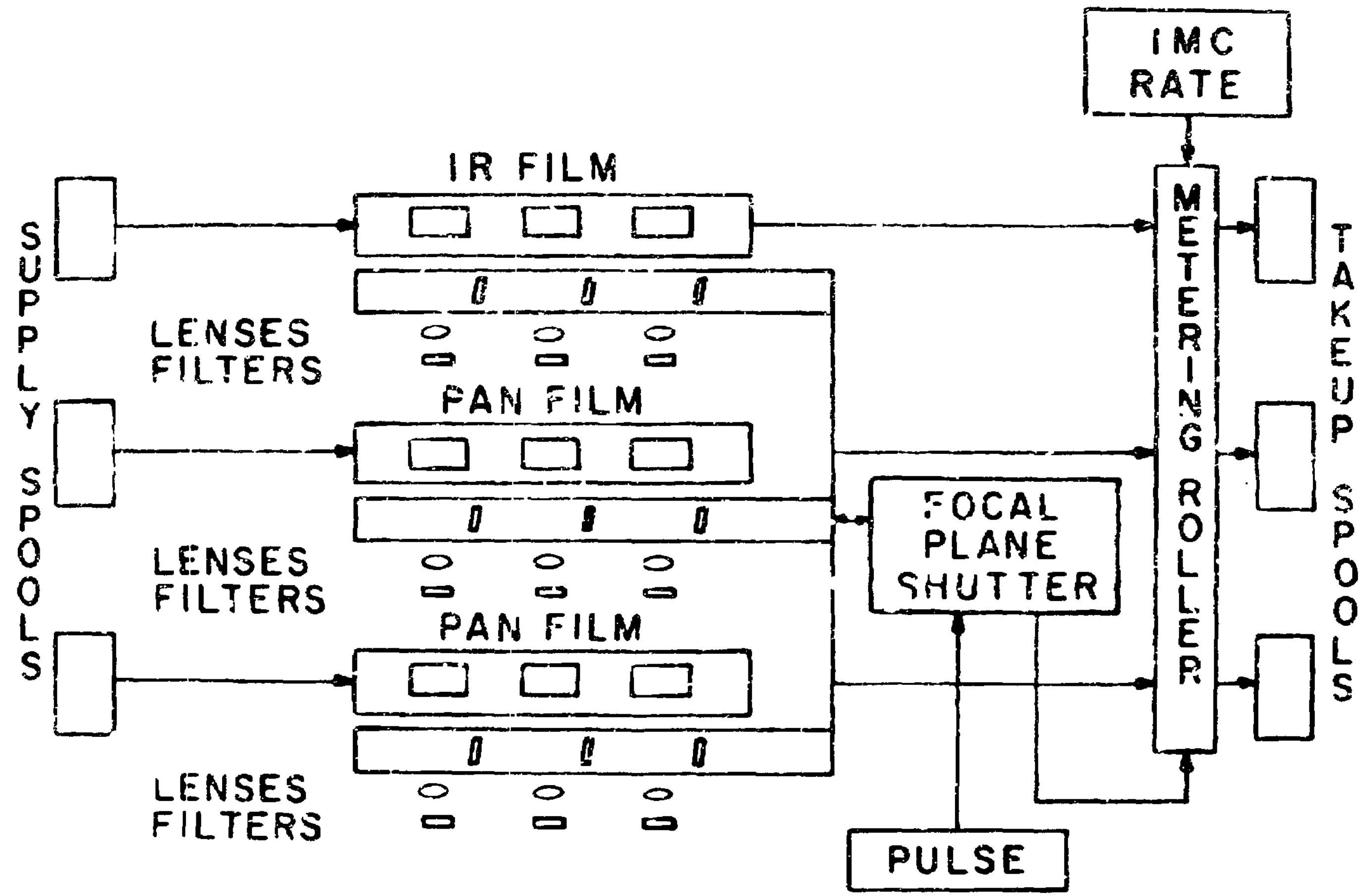

Figure 28 - SFECTRAL CAMERA

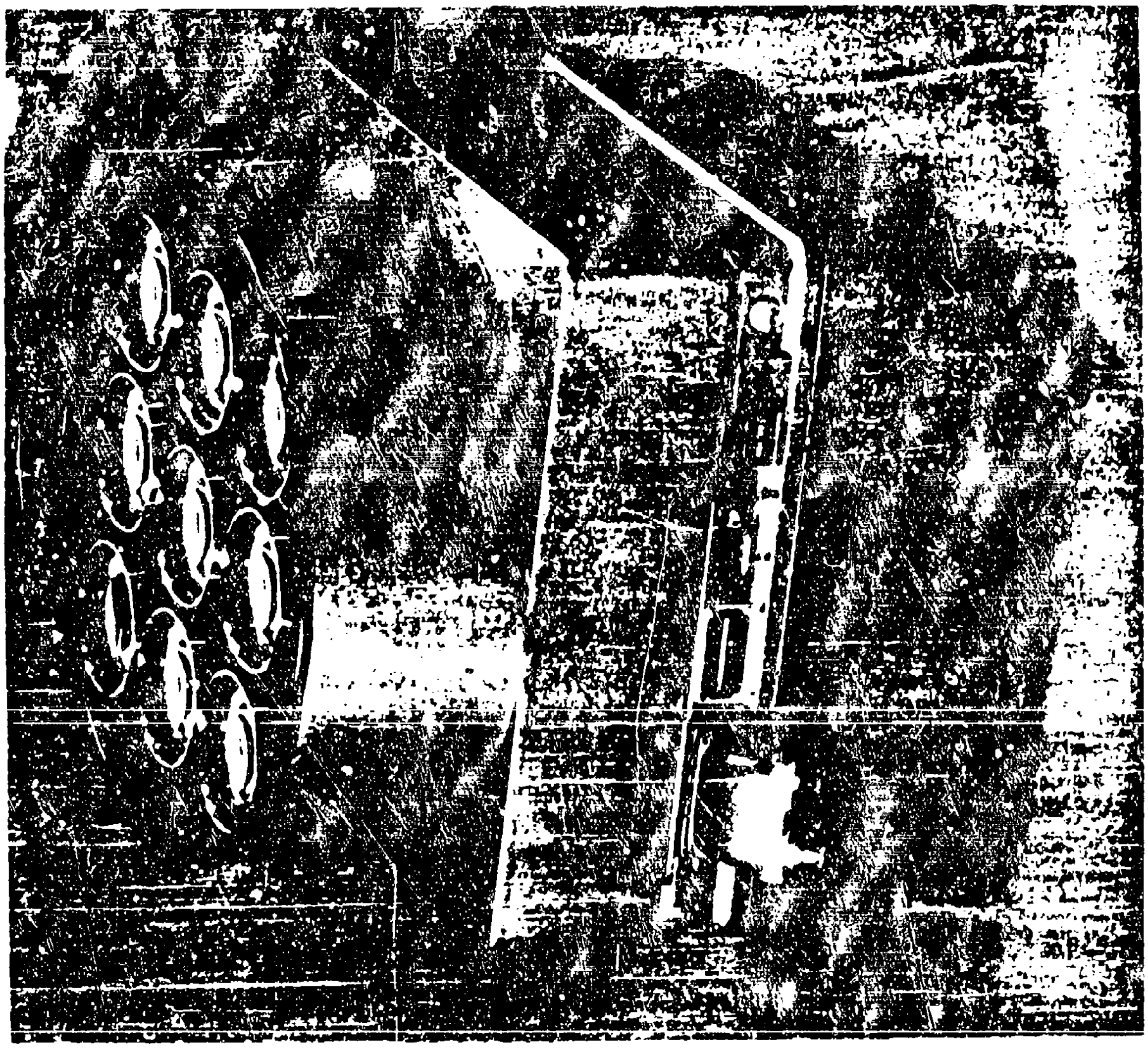

Figure 29 - SPECTRAL CAMERA

illumination will come from an integrating dome which will be exposed to the incident illumination.

When flying this camera at 2,500 feet the object detection sizes mentioned earlier would be obtained.

b. For a second sample, a 24-inch system with five selected multibands will be considered. This sytem will provide equal ground detection at four times the altitude of the nine-lens camera; and with more sophisticated data reduction, a much greater improvement can be obtained.

A dichroic beam splitter system could be used for multiband selection. The component lineup would be as follows.

(1) Three lenses, 24-inch focal length (matched at required wavelengths)

(2) Three films (Plus X, infrared, SO 132)

(3) Five spectral bands

(4) Strip camera drive system

The camera would use dichroic mirrors to divide the input from one lens into three bands. The second lens would expose two bands onto infrared film by the use of dichroic mirrors. The third lens would be of highest quality and would take a normal aerial picture on high resolution SO 132 film. In the color separation work for tonal enhancement, the high resolution image would be superimposed onto the color derivatives to provide the detail lost by the other films. All three films

would be driven by the same master drive roller and, therefore, would be exposed simultaneously and at the same IMC rate. From knowledge to date the bands might be No. 1, No. 3, No. 5, No. 6, and No. 8 (Figure 27). A more detailed analysis of the terrain in question would be required before final selection of the bands could be made.

4. Analysis Techniques

Two data reduction techniques will be explained that will enhance and provide signatures of the terrain so that interpretation may be made as to the soil moisture, drainage conditions, type and density of vegetation and difficulty of topography. These techniques will require specialized equipment, and interpretation of the results will provide new keys for the photo-interpreter to learn.

a. Photo Spectrogram Signatures

By calibration of the spectral camera system and recording of an incident illumination light patch, the relative brightness of any object appearing in the photograph can be determined. Figure 26 displayed an eight-point spectrum; the same technique could be carried out with a five-point spectrum, the five points being those most subject to change with soil moisture, vegetation type, and condition.

By the use of multiband sensitometry a density vs. exposure curve would be derived for each filter combination (Figure 30). This would be done to calibrate the entire camera optical system. Parallel and

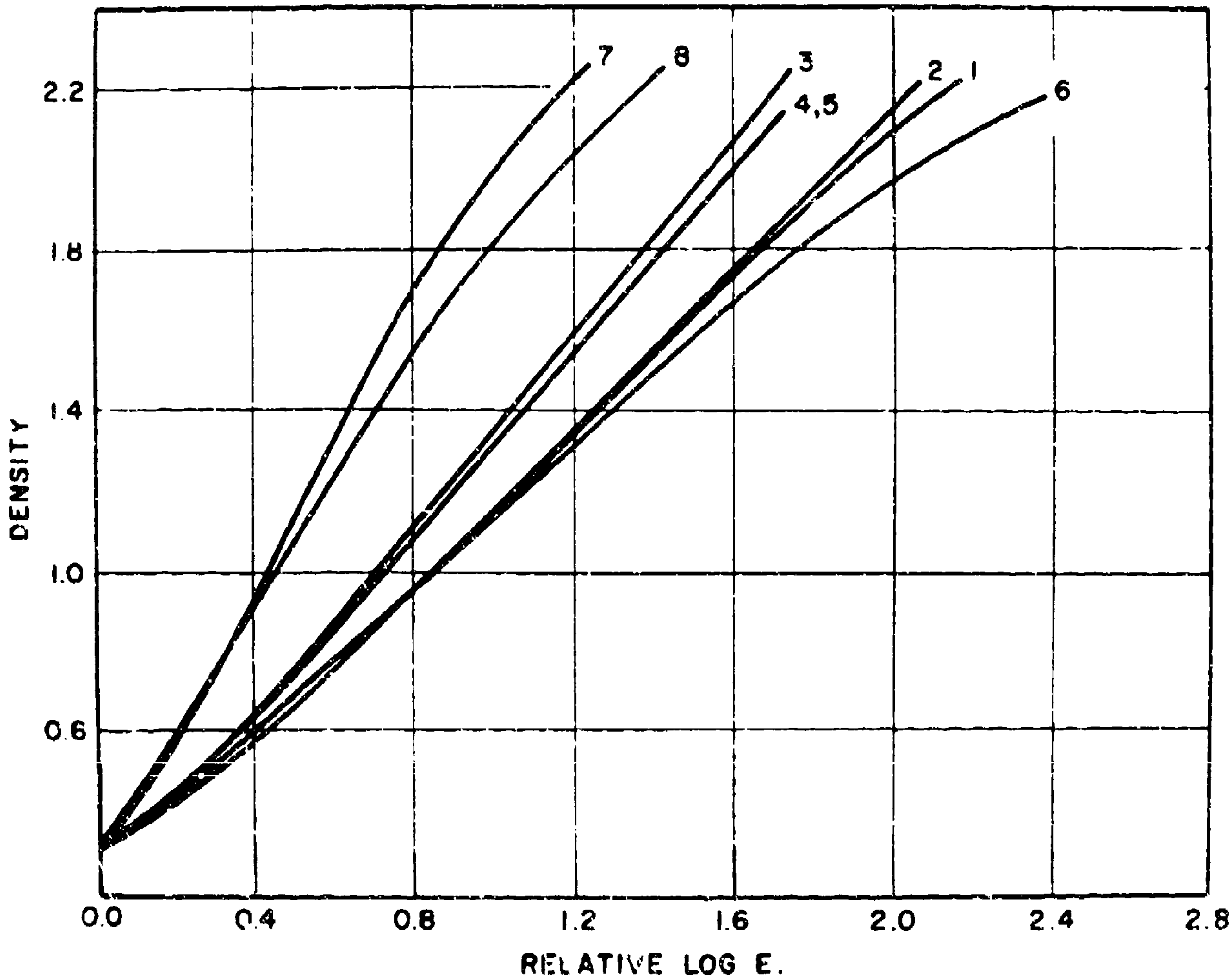

Figure 30 - DENSITY EXPOSURE RELATIONSHIPS

similar processing of the density-exposure information along with the flight film would be performed. After selection of objects for signature analysis (performed by viewing high resolution film) the densities would be read on all the multiband films. The densities would then be con - verted to exposures by the D Log E curves. A comparison would then be made between the exposure of the light patch and the objects for each multiband negative. These exposure differences would be plotted as a signature spectrogram for each area. The exposure differences would provide relative log brightness between the object and the incident illumination for each multiband. The varying color temperature encountered during different flight conditions would be eliminated by the use of the incident light patch as a standard. Interpretation of these results will be mentioned in the next section.

b. Color Derivatives for Spectral Enhancement

A trained and perceptive human observer is irreplaceable in such an analysis. To make use of the observer's color discrimination, the combinations of visual and infrared band separation pictures will be combined and viewed in color.

We are trying to detect subtle effects. Therefore, we must use sophisticated techniques in making use of the raw data provided by the spectral camera. To increase color sensitivity, masking and super-imposition printing techniques will be used.

Work is now underway to devise and test various superimposition techniques using the output of a nine-lens multiband camera. To

enhance the color information the gross brightness variations in the scene are being masked out. This is possible by the printing of positives, with a selected gamma and straight line characteristics, from selected multiband negatives and then by superimposing various combinations of negatives and positives. By printing these superimposed combinations with colored light onto color film, various colors can be obtained for the relative brightness differences of the objects in the various multi-bands.

An observer trained to view this color system will be able to note slight spectral differences of the objects under consideration.

E. INTERPRETATION

All objects have certain reflectance characteristics which are variable with wave length. This relationship within the visible spectrum along with the spectral quality of the illumination determines the color of the object.

The two data reduction techniques described previously are means by which differences in reflection in certain parts of the spectrum can be made more recognizable to the photo-interpreter.

The signature spectrograms would be viewed in conjunction with color film obtained from an auxiliary camera or high resolution film as would be obtained from one of the sample systems. The spectrogram is analyzed and this information, when correlated with what can be interpreted from the photography, will allow the photo-interpreter to make a better judgment as to the nature of the object, especially the

type of material from which it is made.

With a library of spectrogram "keys", that is, signature spectrograms of various plants, soil types, rocks and other natural objects, the spectrograms obtained from the objects in question would be compared to the keys. The object would be identified by the key and by visual means with the color or high resolution photo. The agreement of the interpretations would increase the confidence level of the decision.

Color enhancement signatures obtained from the color derivatives would be viewed in conjunction with high resolution black and white or other color film, as will be done in the existing nine-lens camera system. Once the color enhancement parameters are determined for a given system, the relationship of relative brightness difference between bands to the color obtained on the film will be known. Since this technique will enhance certain spectral distribution conditons, a better identification of the nature of the objects under consideration can be made. As an example, high resolution stereo photographs could indicate the presence of some sort of scrub growth on a land area where a runway is required. The color-enhanced picture would aid in identifying the plant type and the moisture conditions of the terrain on which it was growing. Color "keys" required for this operation would be obtained after the system is calibrated and test flights are made using known ground conditions.

In the preceding sections on the spectral camera it was pointed out that with existing data-handling equipment the ground resolution possible with color enhancement is much better than that obtained with

the spectral signature method. Therefore, cross-correlation between the two methods can only be obtained for objects that are large enough to undergo spectral signature analysis. Most items would be of this size or larger if the scale factor is kept above 1:5000. Being able to compare the results of the two techniques would provide more reliable conclusions as to the nature of the terrain.

The errors possible in the spectral signature method are mostly ones of measurement, recording, and data extraction from curves. The color system lends itself to errors in exposure and development of films and misregistration during superimposition printing. Because of the unlike errors, the agreement of these two entirely different systems would help to validate the interpretive conclusions made.

In conclusion, it should be pointed out that both data reduction techniques are now in the design and testing stage and that special training of personnel to use these methods will be required before they can be put into an operational state.

III. EXPERIMENTAL FLIGHT TEST PROGRAM

After a careful review of the requirements for achieving ground property measurements and the available equipments, the following experimental flight test program is recommended. The program can be divided into four phases: (1) Procurement, modification, and assembly of equipments, (2) Aircraft installation and shakedown flights, (3) Calibrated Test Range Flights, and (4) Data reduction and analysis.

All of the equipments, both airborne and ground, are available either through Government agencies or from manufacturers who have previously produced like items. The modifications required of the units and the aircraft mounts are fairly straight-forward engineering tasks. The proposed program should represent a moderate cost in comparison to the potential results to be realized in confirming the applicability of the system concepts to the terrain analysis problem.

The equipments and test plan recommended here have been greatly influenced by the experience and knowledge gained from the VELA UNIFORM Project now being performed by Itek under Contract No. AF 33 (657) 7381.

A. AIRBORNE SYSTEM

The USAF RC-130 aircraft is recommended as the most suitable vehicle for installing the proposed system. An installation plan is shown in Figure 31, utilizing the existing mounts and space in the most advantageous manner.

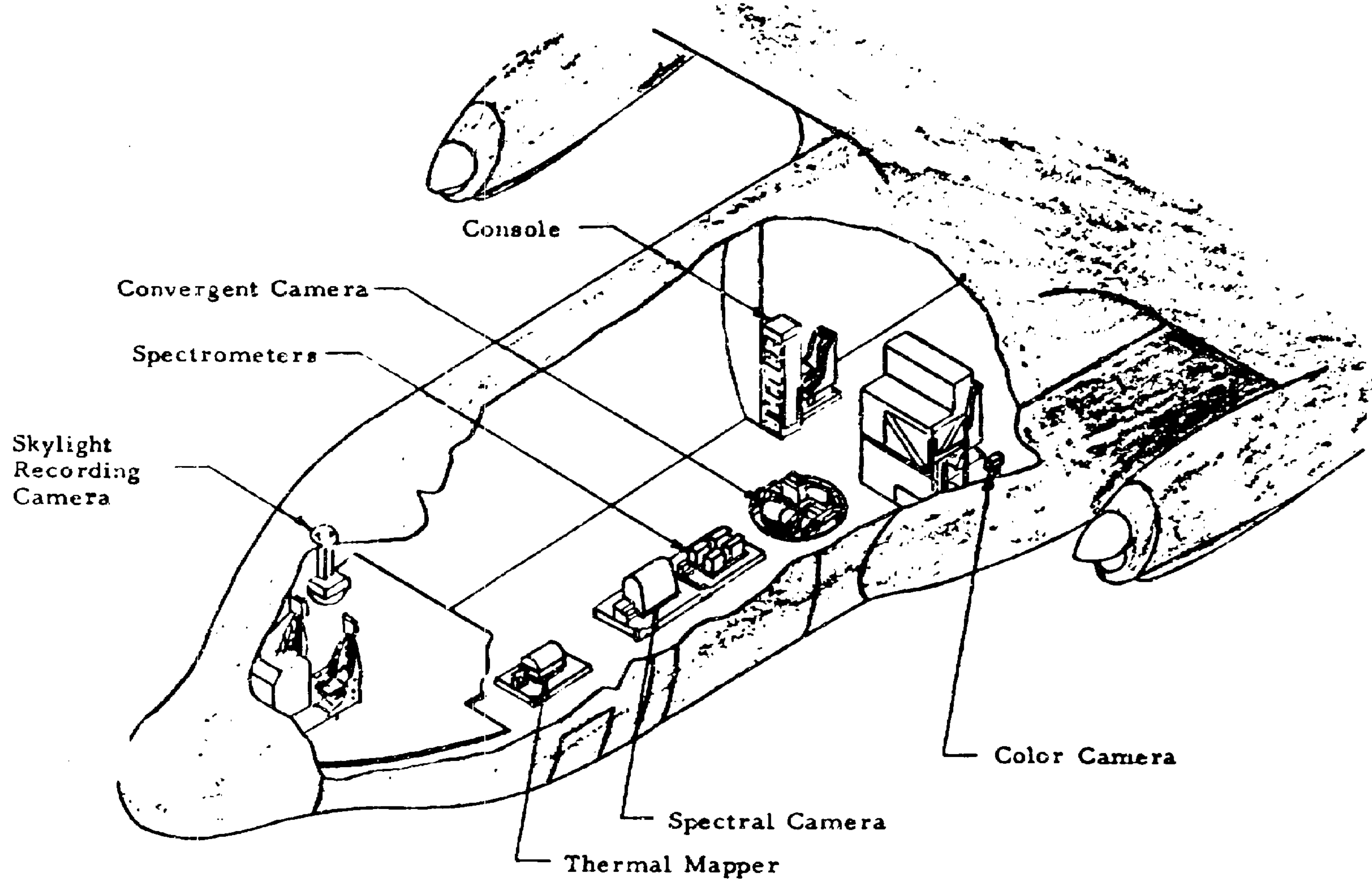

Figure 31 - RC-130 INSTALLATION

A brief description of the equipments to be installed and their characteristics is given below.

1. Skylight Recording Camera

Modified P-2 camera which contains a fiber optic bundle that views the sky and exposes multiband films through various filters. A P-2 camera is being modified for this operation under the VELA UNIFORM Program. The assembly of another unit will fulfill this requirement.

2. Spectrometers

Four Block Associates Spectrometers

(1) Silicon detector 0.4 - 1.0 microns

(2) Lead Sulfide detector 1.0 - 3.0 microns

(3) Indium Antimonide detector 3.0 - 5.0 microns

(4) Thermister detector 8.0 - 13.0 microns

The glass window which normally covers the RC-130 camera port must be removed. The listed spectrometers, except for the fourth unit, are being used on the VELA Program. The present mount is designed to accommodate four units and therefore could be used for this text. The required data reduction system is also assembled and will be operating under VELA direction.

3. Convergent Camera

LG-77A, 48-inch, f/4 camera developed for the RB-57 Baloon Experiment Program will be used. The convergent camera recommended will fulfill the focal length and resolution requirements outlined in Section I of this report. For cartographic purposes the camera should contain a between-the-lens shutter. From examination of the lens design, a louver type shutter could be installed in the large air space between the two sets of four elements. A special rocking mount for IMC would be required as the IMC movement of the film platen would not provide the required fudicial registration accuracy.

4. Control Console

Contains tape recorder for spectrometers, spectrometer pre-amps, V/h and other associated controls. The existing VELA console design with slight modifications to accommodate the extra equipment, would suffice for this portion of the payload.

5. Thermal Mapper

HRB Singer Reconofax or later classified versions will be used. The mapper would be keyed to operate in conjunction with the other spectral payload components. Since real time readout is not required, the unit could operate in the "dry" condition. This item could be obtained on loan as Government-furnished equipment.

6. Spectral Camera

Nine-lens spectral camera operating with three rolls of 70-mm film. This camera could be obtained from the VELA system as Government-furnished equipment or another unit could be manufactured from existing drawings. A rocking mount for IMC would be required. The existing unit operates with internal IMC, but it is felt that rocking IMC with a fixed film-fiducial arrangement would improve the ease of image super-imposition during data reduction.

7. Color Camera

A 220 camera using Ektachrome or camouflage detection film. The existing control console and associated equipment contain a timing mechanism to trigger the color cameras used in the VELA Program in synchronization with the spectral camera. The color camera required could be operated from this circuit. A rocking mount would be required for maximum resolution but satisfactory results could be obtained without IMC.

Figure 31 shows the suggested layout of the payload components in the RC-130. The spectrometers, convergent camera and spectral camera would be mounted over existing viewing ports. The color 220 camera would be mounted in the standard P-2 camera mount at the chief photographer's rack. The thermal mapper would replace the APR receiver-transmitter and antenna. The skylight camera is designed to be inserted in the sextant mount and triggered at that position at the

required times during the flight. This arrangement is similar to that employed in the VELA configuration. The RC-130 provides ample room for installation and operation of the equipment.

B. FLIGHT TESTS

1. Test Plan and Operations

To accomplish the principal objectives of this program, it will be necessary to conduct a series of experimental tests where the proposed airborne sensors are flown over a calibrated test range under controlled conditions.

Although recognizing that the purpose of the program will be to develop identification methods that rely as little as possible on previously obtained intelligence or technical data, it is felt that such experimental flights are required to calibrate and "tune" the sensors as well as optimize the data reduction techniques and procedures. The resultant data would serve to evaluate the validity and completeness of the system concepts, equipment, and analysis methods.

An important benefit to be derived from the experimental test flights will be the development of a significant statistical data sample of signature information for various terrain and vegetation conditions either typical of, or analogous to, sites where actual operations might be required. Through comparative inspection and evaluation methods, ground features may be uniquely distinguished either individually or collectively under varying spectral conditions.

2. Test Site

Choice of test site will be dependent upon such factors as availability of Government or commercial areas, type of terrain and vegetation present, time of year, geographical location, personnel and equipment facilities, and proximity to airfield.

Many of the areas adjacent to and part of existing USAF bases could be utilized, providing most of the above mentioned conditions were satisfied. One of the prerequisites to selection of a test site is to specify the exact terrain and vegetation conditions to be investigated, and then examine in detail the topographic maps and existing photography of the areas under consideration.

A commercial test site that may be worthy of further investigation is Systems Test Facilities located near Grand Junction, Colorado. This newly developed site designs, operates, and maintains testing facilities for both airborne and ground camera systems. An extensive array of test targets are available for resolution, spectral,and infrared reconnaissance.

3. Calibrated Test Range

The detailed requirements for a calibrated test range must finally be determined by the airborne system equipment specifications. However, there are certain basic types of targets that are recommended.

a. Resolution Targets -

These should be both high and low contrast-type targets having a range of bar sizes to accommodate the expected resolution limits of the sensors over the range of flight altitudes.

b. Ground Control Targets -

These should be of sufficient size and contrast to allow easy identification on the cartographic photography. Placement and number of targets will be defined by the area coverage of each model of the convergent photography at each flight altitude. Both center-to-center distance and elevation measurements should be known.

c. Painted Panels -

A series of wood panel targets are recommended as one means of calibrating the spectral system. The targets should be of sufficient size to be adequately resolved photographically and to be measured with the system data reduction equipment. In addition to a gray scale panel, selected colors of paints to cover the visible spectrum should be used on the panels. Samples of the painted panels should be tested for their absolute spectral response in order to provide a basis for calibration.

d. Thermal Targets -

A series of thermal targets are recommended for use with the thermal mapper and the spectrometers. A natural body of water would serve as an ideal calibration source. If none is available on the test site, then an artificial body should be created. Measurement of the water temperature during the time of the flight will be required

Large celotex or other light weight panels painted with white and black paints having known emissivities will also provide calibration information. Total ground coverage of these targets should fill approximately fifty percent of the field of view of the spectrometers at the lowest flight altitude. Accurate spectral reflection data of the terrain immediately surrounding the panels must also be known.

e Measured Ground Targets -

(1) Elevations - Exact elevations of the ground areas contained in the stereo models should be obtained by ground survey parties. This information will be required to check the validity and accuracy of the computed elevation differences.

(2) Object Distribution - Measurements and location of various ground objects (rocks, stumps, logs, grass clumps, etc.) in the stereo model area should be made to serve as further checks against the test results.

(3) Vegetation - A field survey to determine both the types and condition of vegetation is required. It is further recommended that a portable spectrometer (Perkin-Elmer) be used to determine the spectral reflection of the vegetation in its natural state. This would also apply to the soil types and conditions to be identified.

(4) Soils - A field survey to determine both the types , condition (wet, dry) and composition (compact, loose) is required. It is further recommended that several areas of soil undergo controlled environmental changes. Examples of such changes are areas whose moisture content can be varied and the exact percentage measured, and areas whose surface characteristics can be varied by compacting, loosening, or spreading lime and other types of materials.

4. Weather Data

In order for the information gathered by the airborne sensors from the targets described above to be properly reduced and analyzed it is necessary that complete and accurate weather and meteorlogical data be gathered at the same time. The proper instruments to sense and record the following types of data are required: temperature, humidity, barometric pressure, wind speed and direction, and cloud cover. Such data should be recorded both at the ground stations and in the aircraft.

Supplementary data in the form of sun angle, color temperature, incident light values as well as the spectral content of the light at the targets, will also be required.

5. Flight Plan

The following parameters are recommended as representative of a flight plan for the test program.

a. Flight Altitudes (In feet)

2,000

3,000 (Spectral Reconnaissance Systems)

5,000

5,000

10,000 (Convergent Camera System)

20,000

b. Flight Speed

150 - 200 miles per hour

c. Flight Times

Morning - 9 to 10 A. M.

Noon - 11:30 A. M. to 12:30 P. M.

Afternoon - 3 to 4 P. M.

d. Target Area

Rectangle oriented generally North - South

Width - To match spectral camera field of view at 5,000 feet

Length - To provide three or four stereo models from convergent camera at 20,000 feet

e. Flight Lines

One (1) in each direction for each altitude

NOTE: Using only one convergent camera, one half of each convergent stereo model will be photographed flying one direction; the other half will be photographed flying in the opposite direction using visual ground check points to obtain proper overlap and cycle times.

6. Ground Facilities

Facilities for storing checkout, and maintenance of the system equipments are required at the airfield where the aircraft is based. The following is a representative list of items to be included.

Hand tools

Power supplies

Test and checkout equipment

Spare parts

Film storage

Dark room and processing equipment

Since the concept of the spectral reconnaissance system is based upon slight differences in the film densities, it is mandatory that the processing be performed under controlled conditions. It is, therefore, recommended that all film be shipped to a first class photographic processing facility and preferably the one where the data reduction and analysis operations are to be carried out.

The necessary equipment and instruments for preparing and maintaining the calibrated test range as well as reading and recording the required control data must be on hand at the test site.

7. Personnel

Minimum personnel requirements to conduct the test program after calibrated range is functioning and airborne systems have been installed initially are as follows:

a. Field Operations:

Aircraft Liaison Engineer

Test Site Liaison Engineer

Photo-optical Field Engineer - Flight Equipment Operator

Photo electrical Field Engineer - Flight Equipment Operator

Field Engineer - Test Site (2)

Aircraft Crew

b. Data Analysis:

Test Director (same as above)

Photographic Technicians (2)

Electronic Technician (2)

Photo Interpreter

Photogrammetrist

Computer Programmer

8. Test Operations

It is recommended that a minimum of five days of photographic flights be conducted over the calibrated test range in order to provide sufficient data to provide a valid statistical sample of system errors and "noise". An additional two or three flights over terrain which has no artificial targets or control points is recommended upon completion of the primary flights. Such flights should provide data representative of future operational flights and will allow further refinement of data reduction and analysis techniques and procedures. Test personnel and equipment should be retained at the site until all flight data has been processed and it is determined that all required information is available to proceed with the data analysis operations.

Requirements for the utilization of the system which has been outlined in this report under actual operating conditions will undoubtedly specify year round utilization. In order to provide the experimental data and determine the signatures and keys to satisfy these requirements, it is recommended that the test plan be conducted at approximately three month intervals for a period of one year.

9. Data Analysis

a. Photogrammetric Data Handling

The convergent photography obtained during an operational flight should first be analyzed carefully by experienced and well-trained photo-interpreters. Through this preliminary step, those areas in which large and easily recognized elevation changes occur can be immediately eliminated as possible sites for aircraft landing operations. Only the relatively flat, questionable areas which remain will require precise photogrammetric analysis. This procedure should also be followed under test conditions. The results of this step will be extremely useful in accurately determining the interpretability of specific terrain details for given flight and terrain conditions.

The maximum information available for this analysis is obviously that recorded on the original photographic negative. It is inadvisable, however, to release these films to the personnel performing the analysis. The recommended procedure, for both the photo-interpretation and photogrammetric reduction, is to supply the observers with diapositive copies of the highest possible resolution. These should be made on stable films or glass plates by a contact printing process.

As was indicated in Section I. E., the full information content of the photography will only be utilized when the photography is viewed under large magnification. The stereoscopes used for the photo-interpretation, therefore, should be equipped with binocular viewing systems

which will provide enlargements in excess of 10X. Additional information regarding the interpretability of terrain detail may be obtained if this magnification is variable.

Based on the investigations in Section I. E., it is recommended also that the photogrammetric measurements be performed on a precision stereocomparator, and the subsequent elevation computations on a high-speed electronic computer. It is our understanding that equipment of this type is being used by several agencies of the Air Force.

The viewing system of the comparator will require magnifications similar to that of the stereoscopes used in the photo-interpretation. These viewing systems are normally equipped with dove or Amici prisms by which the geometry of convergent photography can be compensated to obtain proper stereoscopic vision. For the limited number of models to be analyzed in the test program, these adjustments may be performed manually. The results of these tests will indicate whether or not modifications will be required in order to automate this correction for an extensive operational program.

The computations will require a computer program which incorporates functions of both the relative and absolute orientations and the capability for introducing known corrections for lens distortion, film distortion, earth curvature, and atmospheric refraction. The leveling and scaling of the model should be performed both with the aid of the ground control available at the test site, and with only the inflight data (camera stability and aircraft altimetry) to be used in an operational program.

An indication of the influences of lens and film distortion, atmospheric refraction, and earth curvature may be easily obtained by running a series of computations with and without corrections for these errors. The possibilities for correcting the film distortions may also be investigated if photography is obtained using the film alone, the film with reseau grid, and glass plates. These latter investigations will only be required, however, in the event that preliminary tests show these errors to have a significant influence.

b. Spectral Data Handling

A general flow pattern for terrain analysis is shown in Figure 32. In previous sections of this report the methods of data reduction and analysis for the output of the spectral camera have been explained. The output of the thermal mapper will be reproduced as a film positive and analyzed for thermal relationships of objects in conjunction with all other spectral data. Figures 33 and 34 show the data reduction equipment and the flow pattern required for the spectrometer output. Figure 35 shows the data display obtained from a spectrometer operating in the 0.4 to 1.0 micron range. Specialized equipments are being built for various phases of the spectral camera reduction and analysis procedures under the existing VELA contract.

As indicated on the Data Flow figure, a final correlation is planned of all spectral information after the individual data are analyzed. It is anticipated that the information provided from the analysis of the individual sensor data would be in substantial agreement in identifying ground

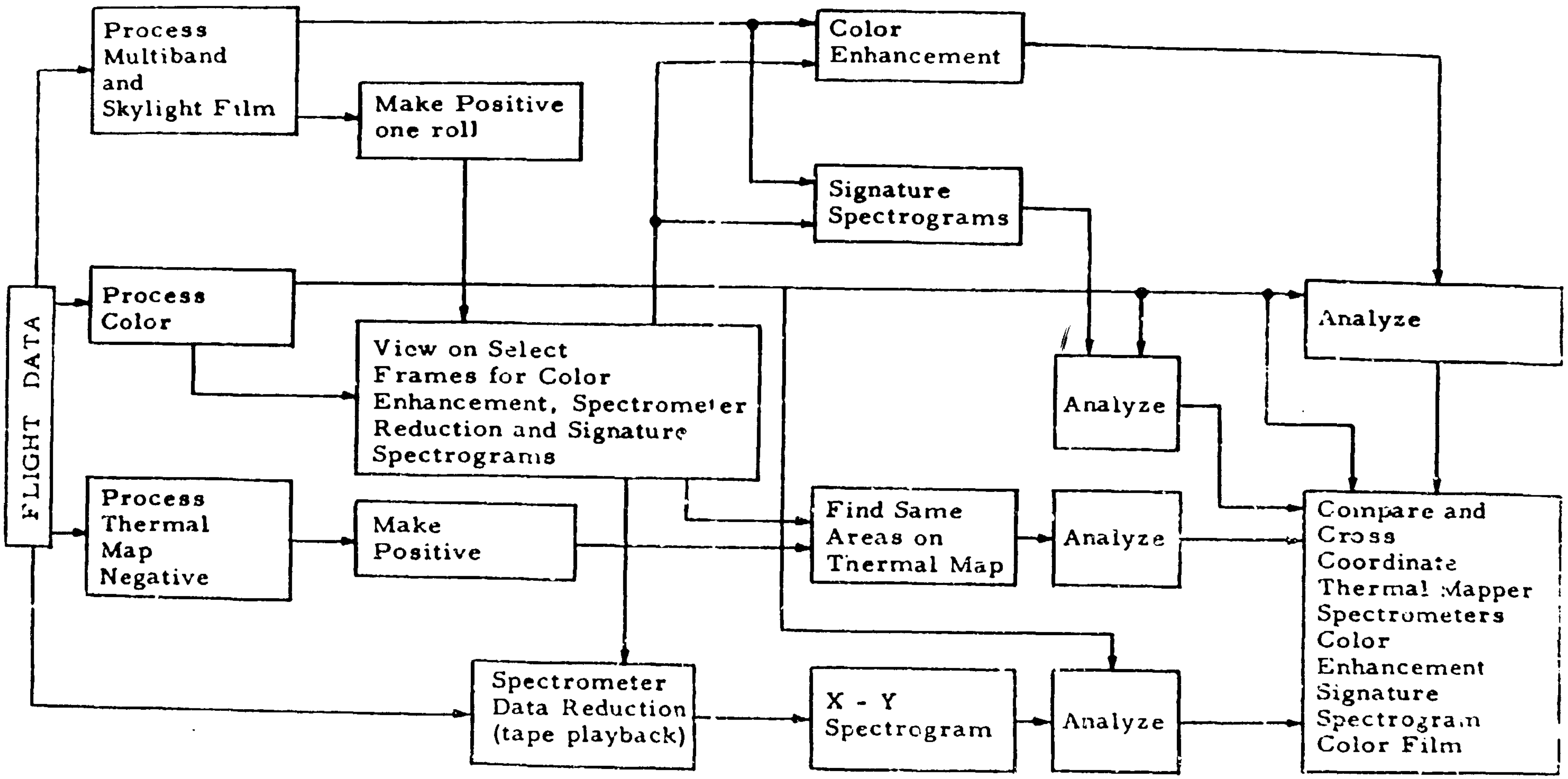

Figure 32 - DATA FLOW FOR TERRAIN ANALYSIS TEST

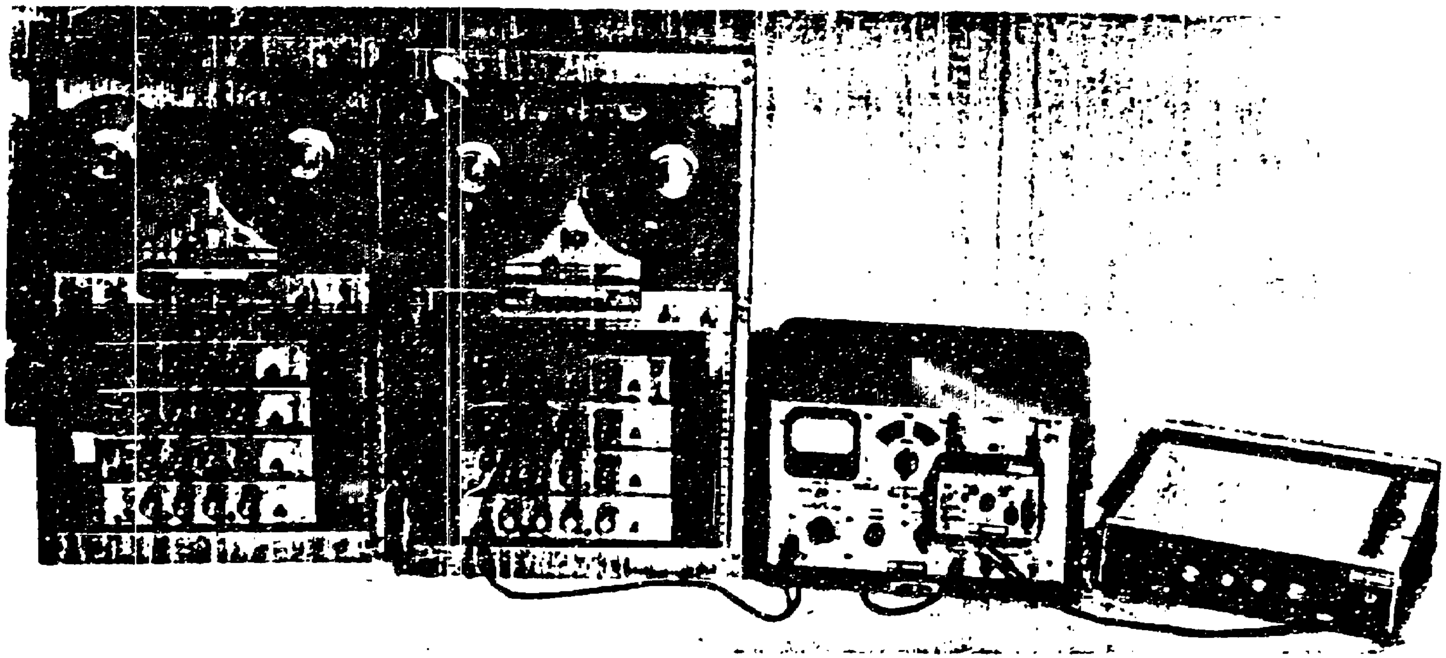

Figure 33 - SPECTROMETER REDUCTION EQUIPMENTS

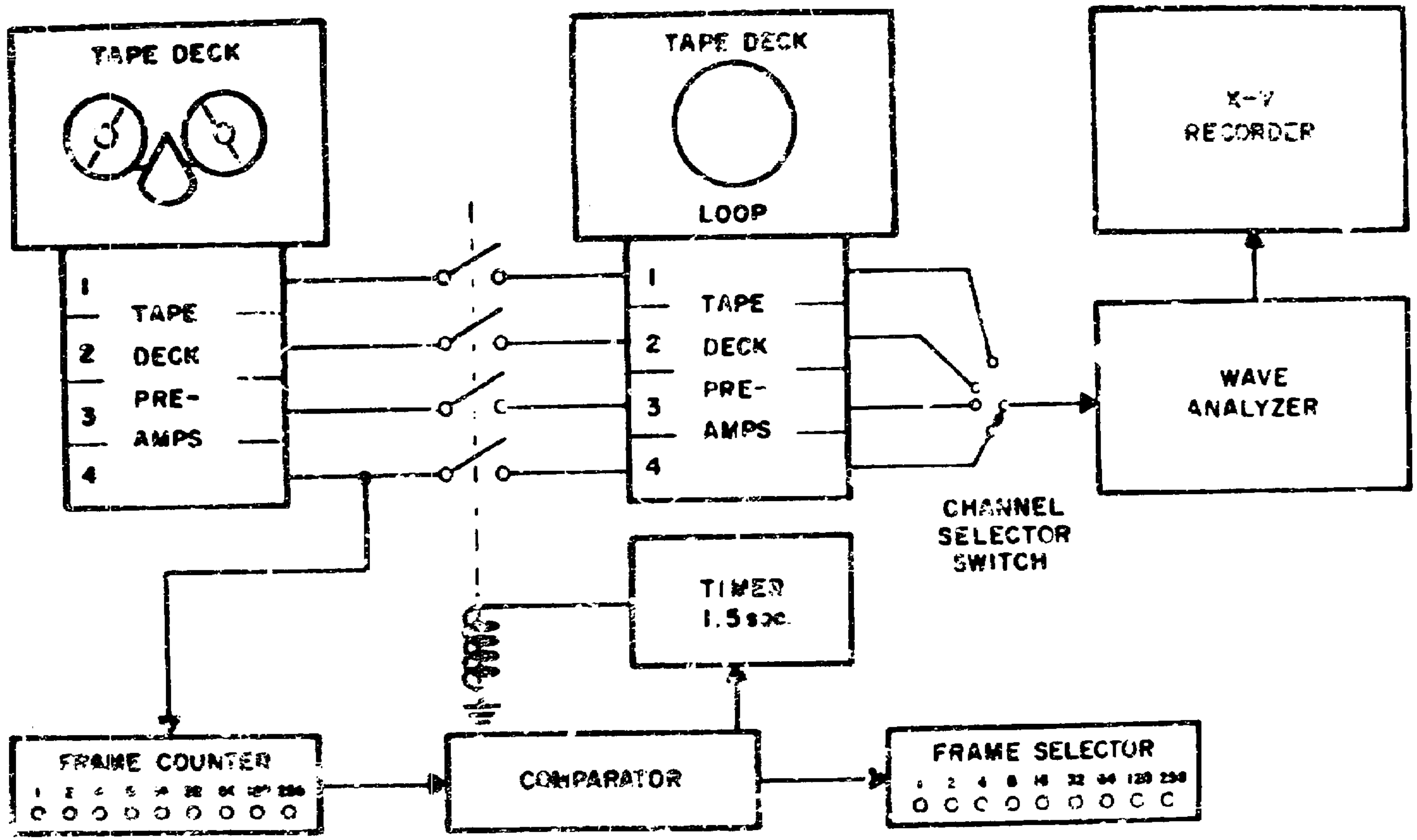

Figure 34 - SPECTROMETER DATA REDUCTION

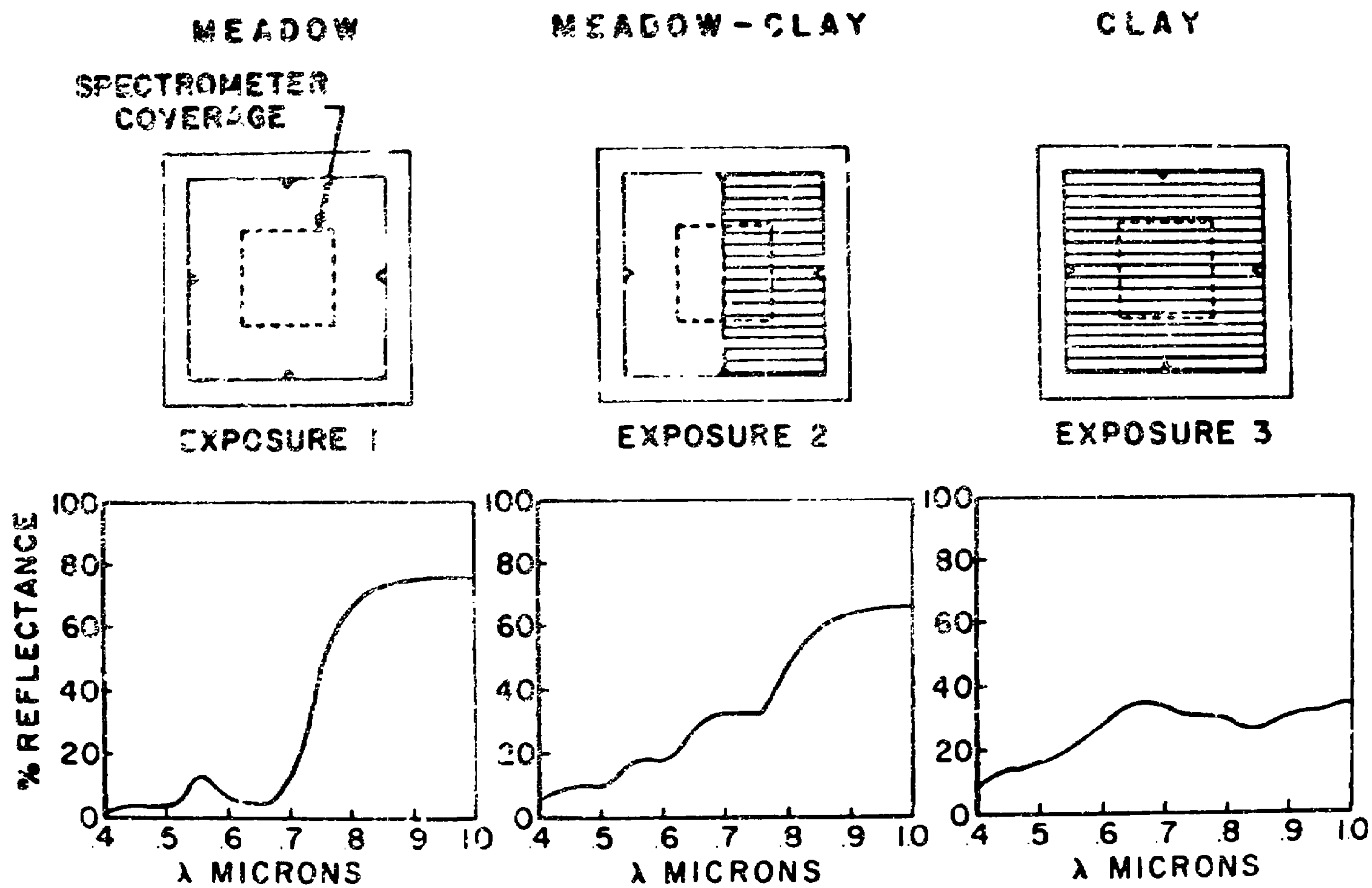

Figure 35 - SPECTROGRAM EXAMPLES

conditions. Cross-correlating two or three of the sensor outputs by certain techniques will provide an amplified result that could not be obtained with individual analysis alone. As in any experiment some disagreement between data will occur and this would be investigated for possible causes.

Since the flight will cover a known test area and a few areas without ground control the following general plan is envisioned. The known flight data will be put through the data reduction system and after correlation, "keys" will be formulated. Then the data obtained from terrain without ground control will be put through the system and the previously determined "keys" will be used for analysis. As verification the ground areas can later be inspected for compliance to test conclusions.

The cartographic data analysis output can be combined with the spectral data analysis in two ways. The first being the conclusions reached from the cartographic analysis would be fed to the spectral analyist to aid him in making his determination about the terrain. The second would be that both analyzing operations would operate in parallel and separately, and upon completion of each, the results would be compared for agreement. Both methods are of value and would be tried during the data reduction operation.

APPENDIX A

DETERMINATION OF SPECTROMETER DETECTOR SENSITIVITY

The sensitivity of the spectrometer to be employed in the 8-13 micron range can be expressed in terms of a minimum detectable emissivity difference at the earth's surface. The emissivity difference is presumed to be a function of different types of objects or terrain or some types of objects or terrain having different conditions, (i.e., wet, dry, compacted, loose, healthy, diseased).

It is usually understood that "minimum detectable" means that the signal is equal to the noise, so that a more correct term might be noise equivalent emissivity change. Expressions are developed below to show the parameters that affect spectrometer sensitivity.

The radiance N of the Earth's surface for a wavelength interval equal to the spectral resolution capability of the spectrometer is given by the following equation:

$$N = (\Delta\lambda)\, N_\lambda = \frac{\epsilon\, \sigma\, T^4}{\pi} \,\Delta\lambda \quad W/(cm^2 - sterad) \qquad (1)$$

Where N is the Earth's spectral radiance W/(cm^2 - sterad - micron), is a typical value of the Earth's emissivity, $\sigma = 5.67 \times 10^{-12}$ Watt/ (cm^2 - deg^4), T is the Earth's temperature in degrees Kelvin, and $\Delta\lambda$ is the spectrometer spectral resolution element in microns. The difference in radiance due to the change in emissivity $\Delta\epsilon$ is:

$$\Delta N = \frac{\Delta\epsilon\, \sigma\, T^4\, \Delta\lambda}{\pi} \qquad (2)$$

The incremental change in energy rate at the input to the optical system is:

$$\Delta P = \left(\frac{\pi D^2}{4}\right)\left(\frac{A}{R^2}\right)\Delta N \tag{3}$$

Where D is the effective diameter of the spectrometer aperture. A is the area of the Earth's surface viewed by the spectrometer, and R is the distance separating the spectrometer from the Earth's surface.

In spectrometer terminology the first two terms of Equation (3) are called throughout (θ_o) with units of (cm^2 - sterad). Equation (3) then reduces to:

$$\Delta P = \Delta N \theta_o \tag{4}$$

Substituting the value of ΔN given in Equation (2), one obtains:

$$\Delta P = \left(\frac{\Delta \epsilon \, \sigma T^4 \lambda}{\pi}\right)\theta_o \tag{5}$$

If we let ΔP represent the noise equivalent power (NEP) of the detector, then the minimum detectable change of the Earth's surface emittance is given by Equation (5).

The noise equivalent power of most detectors varies as the square root of detector area a and electrical bandwidth Δf, i.e.:

$$\Delta P = NEP = \frac{(a\Delta f)^{1/2}}{D^*} \qquad (6)$$

Where D* is the detectivity of a one cm^2 detector for f = 1 cps. In addition, most detectors receive only a fraction F of the total energy emitted by the object (Earth's surface). Thus:

$$\Delta\epsilon = \frac{\pi\,(a\,\Delta f)^{1/2}}{D^*\,\sigma T^4\,\Delta\lambda\,\theta_o F} \qquad (7)$$

where:

$F = N_o N_a$

N_o = optical efficiency

N_a = atmospheric transmission

Since the above parameters are approximately known for the system proposed, the minimum detectable emittance ($\Delta\epsilon$) is .0013. Where a very conservative D* for the thermistor detector is 10^7,

a = detector area = $1/4\ cm^2$

Δf = 15 cycles/sec

σ = $5.67 \times 10^{-12}\ W/(cm^2 - deg^4)$

T = 300°K

$\Delta\lambda$ = 1 micron

θ_o = .1 (cm^2 - sterad)

N_o = .15

N_a = .7

If the minimum detectable temperature change ΔT is derived and divided into the expression for $\Delta\epsilon$, the relation between $\Delta\epsilon$ and ΔT results.

Thus:

$$\Delta T = \frac{T\,\Delta\epsilon}{4} \tag{8}$$

If the average emissivity of the Earth's surface is taken as $\epsilon = .6$, the minimum detectable temperature difference is $.17^{\circ}K$.

The above indicates that a surface object or terrain having an emissivity difference of 0.22 per cent or a temperature difference of only 0.057 per cent is detectable with this spectrometer.

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